Hazard Assessment for the Eemskanaal area of the Groningen field



Eemskanaal Cluster with rig drilling Eemsknaal-13

Contents

Introduction

After an earthquake of magnitude 2.8 on September 30, 2014 in Ten Boer and the subsequent parliamentary debate, the minister of Economic Affairs requested a renewed assessment of the earthquake hazard for the Groningen gas field with a specific focus on the Eemskanaal area around the Eemskanaal production cluster. A review of this area of the field is pertinent because of its relative proximity to the city of Groningen and its unique technical nature, making it more difficult to assess the seismic hazard.

Based on the latest production figures and forecasts and several model improvements a set of seismic hazard maps were generated in order to assess whether there is a significant increase in induced seismic hazard near the city of Groningen.

The Eemskanaal Cluster of the Groningen Field

Groningen production cluster Eemskanaal is a king-size cluster producing from 13 wells. It is located in the south-western part of the Groningen field. Twelve of these wells produce from the Eemskanaal area directly below the cluster. Eemskanaal-13 is a deviated well producing from the Harkstede block located south-west of the Eemskanaal cluster.

Gas from the cluster is produced into the Groningen production ring pipeline. Via the nearby located custody transfer-station Overslag Eemskanaal, the gas is evacuated to the Gas Transport Services (GTS) grid.

The gas produced from the Eemskanaal cluster has a different composition and calorific value compared to the gas from the other Groningen clusters. It has a Wobbe Index of average 45.7, compared to a value of 43.7 for the other Groningen clusters. Groningen gas can only be delivered when its composition is within the narrow Groningen Gas Quality band. The maximum contractual Wobbe value is 44.2. Currently, the Eemskanaal gas can only be produced when it is mixed with a sufficiently large volume of gas from other Groningen clusters.

The Eemskanaal gas is mixed in the ring pipeline with gas produced by other Groningen clusters to meet the gas delivery quality specifications. Consequently, the contribution of the Eemskanaal cluster to the overall Groningen field production strongly depends on the off-take of sales gas on Overslag Eemskanaal by GTS. In periods of low demand, less gas is available for mixing with gas produced from the Eemskanaal cluster.

Currently, the technically maximum Eemskanaal capacity is estimated at 17 million Nm^3/d without the quality constraint. Under current operating conditions for the field offtake, the production is estimated to be, approximately 8 million Nm^3 per day on a monthly averaged basis.

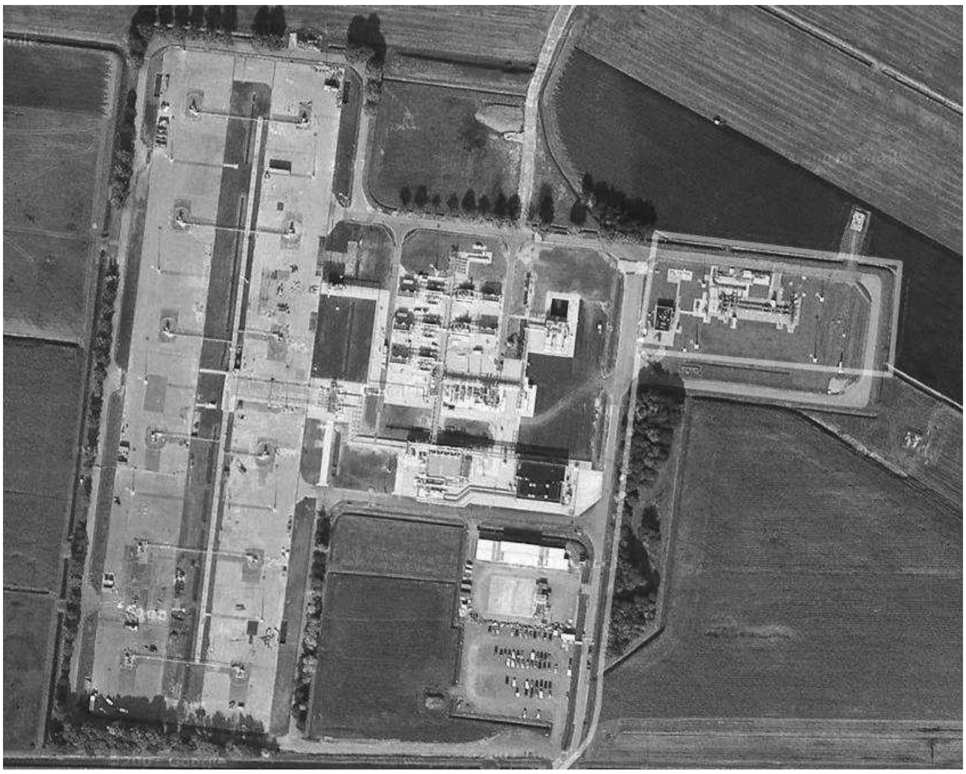


Figure 1 Areal overview of the Eemskanaal Cluster

Subsidence observations in the Eemskanaal Area

Gas production from the Groningen field leads to subsidence at the surface. Subsidence in the Groningen field area is monitored since 1964 through levelling surveys, and since 1992 also through satellite observation. The monitoring capacity was further extended in March 2013 with the installation of two GPS stations at the Ten Post and Veendam production locations. Ten additional GPS stations were installed early 2014 (Figure 2).

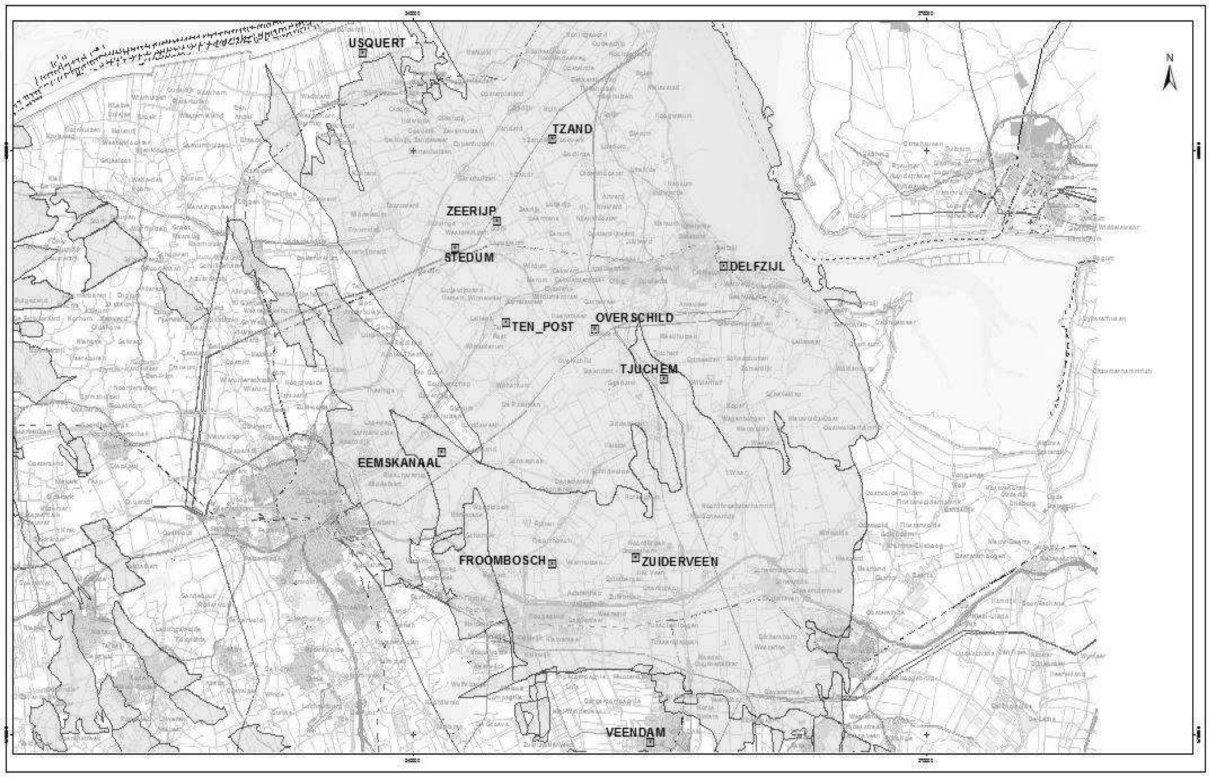


Figure 2   Location of the 11 GPS stations for subsidence monitoring in the field.

One of the new GPS stations was placed on the Eemskanaal cluster. Data obtained from this station indicate a subsidence of some 5 mm at this location for the period from 20 February to 28 September 2014, (Figure 3 and 4) .

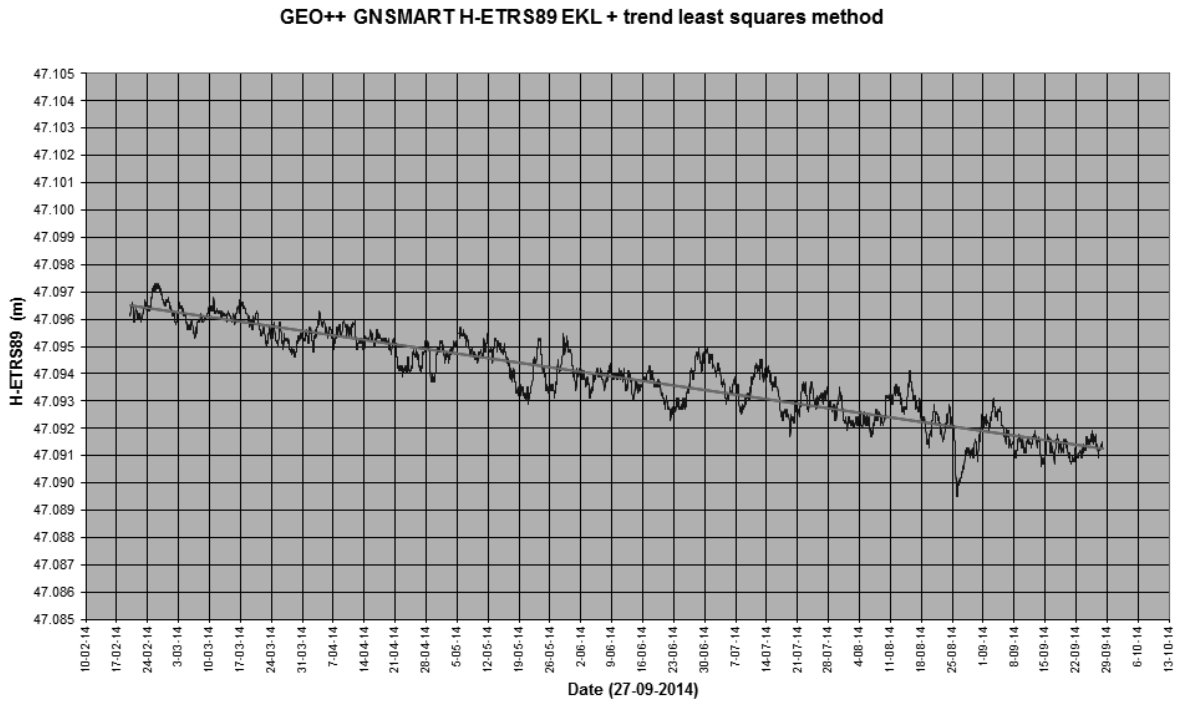


Figure 3 *Results from the permanent subsidence monitoring GPS station at the Eemskanaal Cluster.*

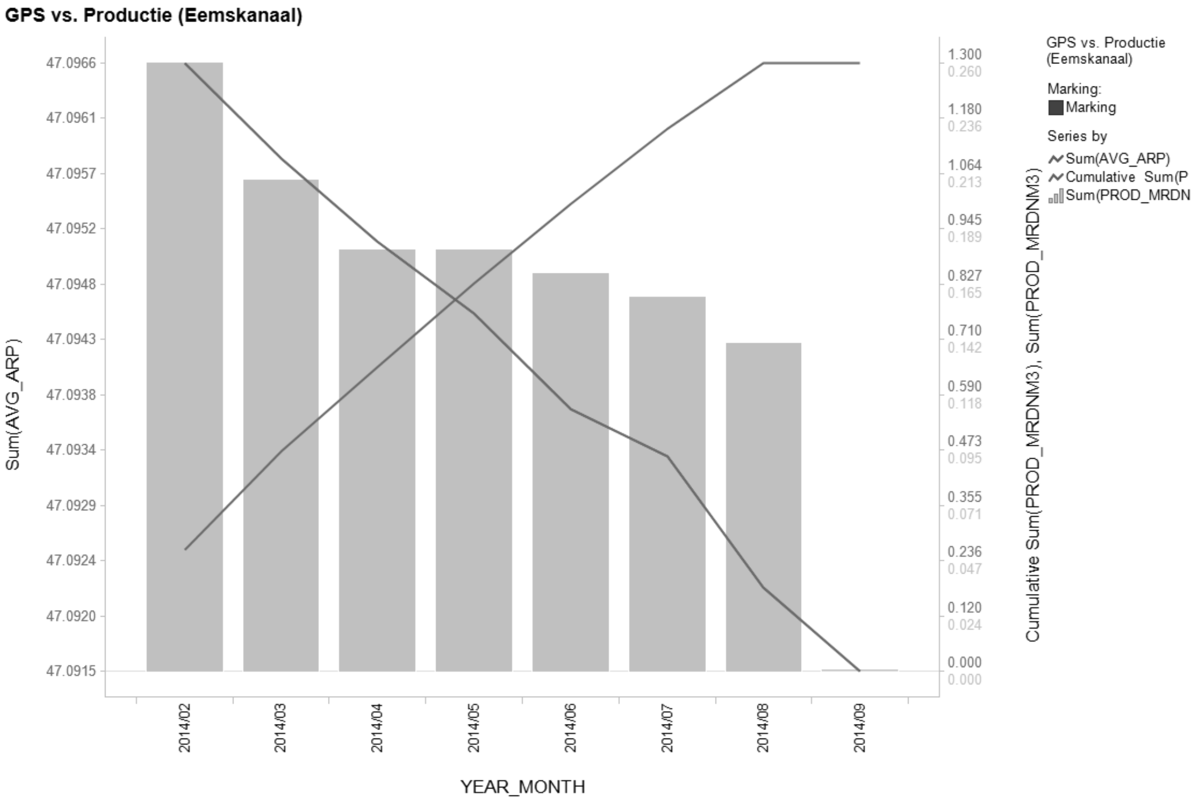


Figure 4 *Estimated subsidence at the Eemskanaal Cluster location since the installation of the GPS station in February 2014. Production from the Eemskanaal Cluster is also shown.*

The levelling surveys meet the specifications for monitoring of NAP set by Rijkswaterstaat. These specifications have been prescribed in 'Productspecificaties Beheer NAP, Secundaire waterpassingen t.b.v. de bijhouding van het NAP, versie 1.1 van januari 2008'.

The results of the levelling surveys are made available to SodM in the form of a state of difference (differentiestaat). This includes the levelling data obtain by or commissioned by Rijkswaterstaat. The state of differences is based on estimated heights, using a free network adjustment, for each epoch. Identification errors in the historical measurements have not been removed. This means outliers can occur in this data. Furthermore, no distinction has been made between autonomous movement of the levelling benchmarks and movement as a result of gas production.

The movement of a levelling benchmark located in the Eemskanaal Area is shown in figure 5.

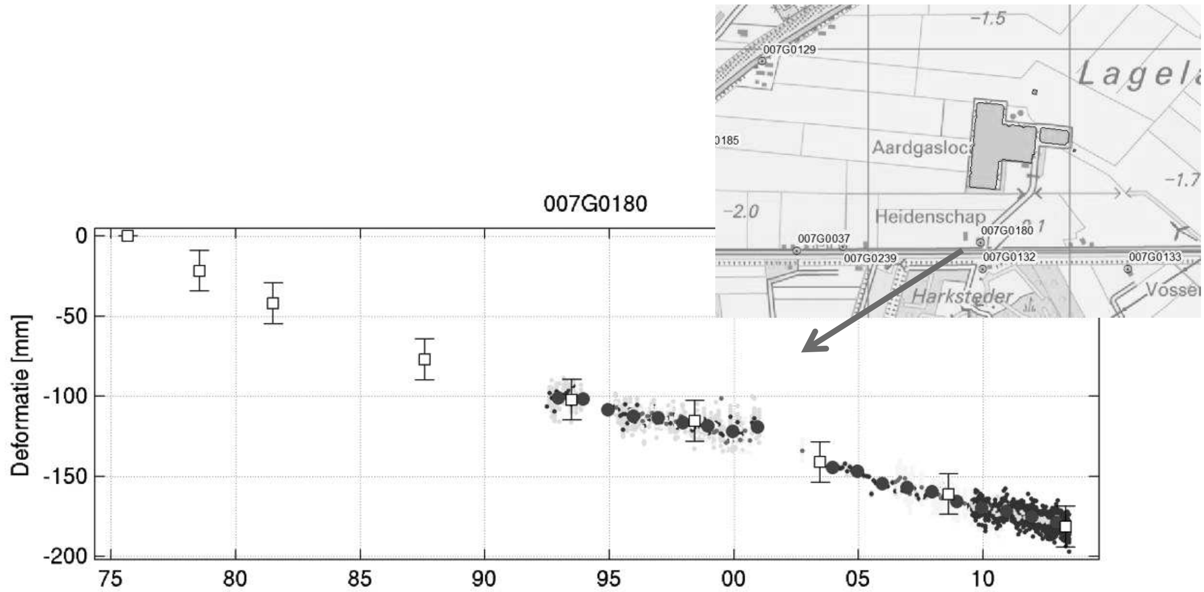


Figure 5 Example: Levelling benchmark 007G0180 located south of the Eemskanaal Cluster location shows good correspondence between the subsidence measured by levelling surveys [white squares with uncertainty indication] and satellite measurements [green circle markers indicate one-year averages].

An overview of subsidence measured in the Eemskanaal area in the period 2007 to 2012 is shown in figure 6. This shows good correspondence between levelling survey results and satellite (InSAR) measurements.

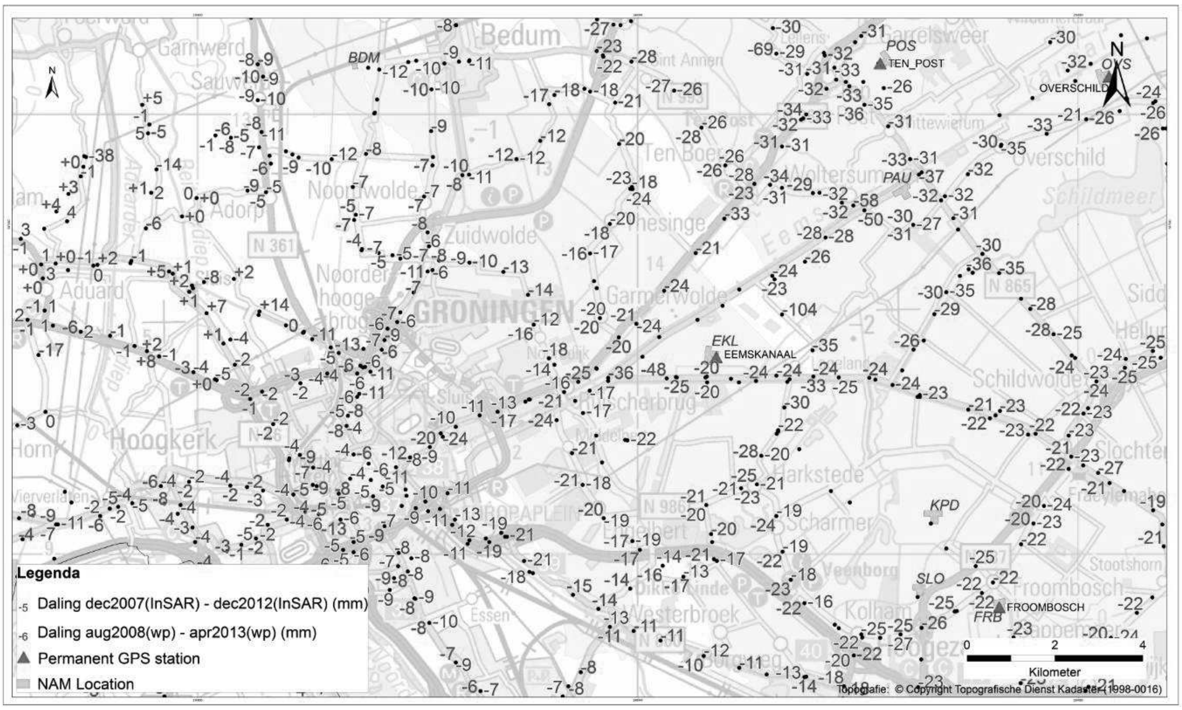


Figure 6 *Subsidence measurements in the Eemskanaal Area from levelling surveys (red) and satellite measurements (blue) over a 5-year period (2007 – 2012). Values (in mm) represent the change in relative height that occurred over the 5-year period.*

Benchmark stability can be an issue. This is illustrated by the two example benchmarks discussed below.

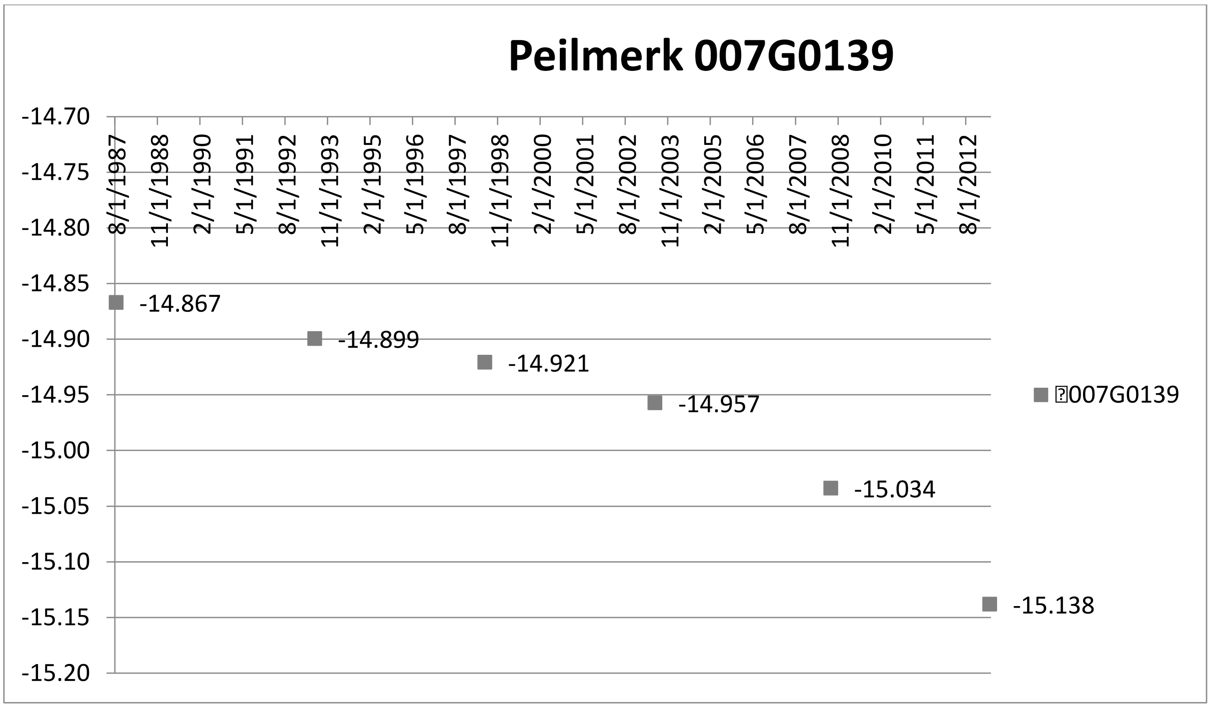


Figure 7a *Levelling benchmark 007G0139 north-east of the Eemskanaal cluster shows high subsidence while surrounding benchmarks show subsidence in line with the regional trend. Also in the period 2003 to 2008 this benchmark showed large height reduction of*

77 mm. This very localised effect is not thought to be the result of gas production. (values relative to reference benchmark (m))

Further desktop investigation showed cracks in the wall, where the benchmark is situated, which might imply the instability of the building (see photo below; benchmark is at lower left, at the white circle)



Example of close-by benchmark 007G0214 (this mark is located ~1.3km from 007G0139), which shows a constant deformation over time.

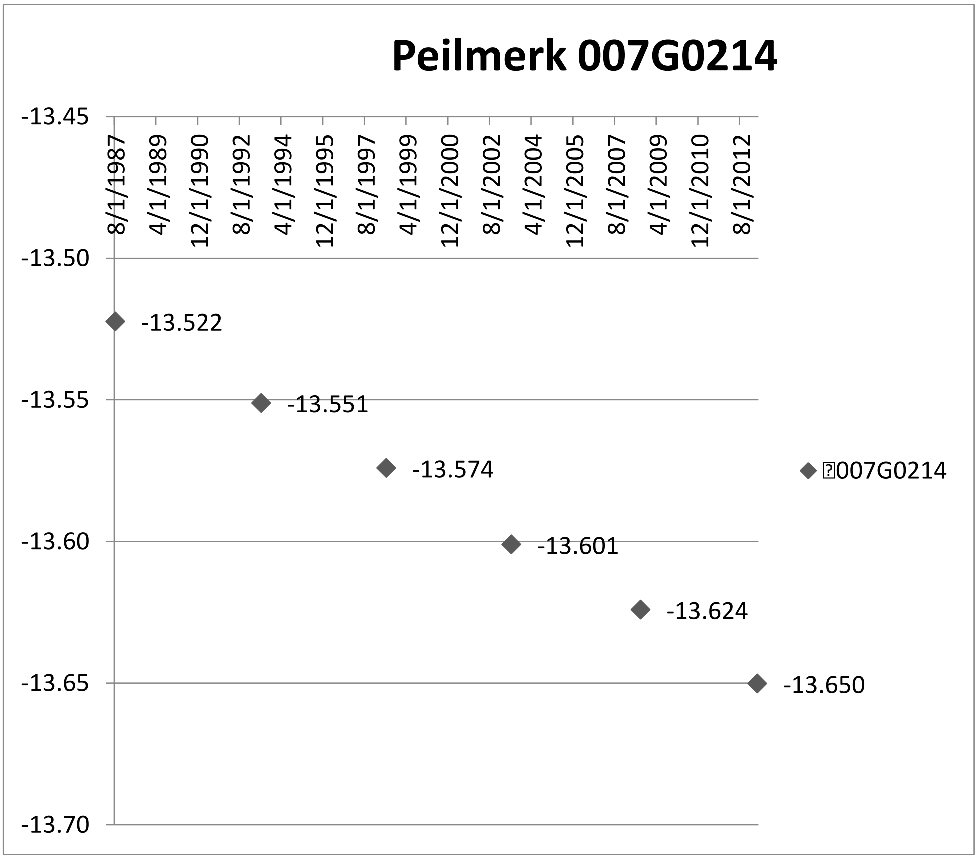


Figure 7b Levelling benchmark 007G0214 approx.1.3km north-east of 007G0139 shows a constant deformation over time. Lineair velocity ~5mm/yr.(values relative to reference benchmark (m))



Groningen Field Model

General

Calculation of seismic hazard is based on output from static and dynamic models. Results from the Groningen Field Review (GFR2012) used for the update of the Winningsplan 2013, showed a relatively poor match in the south-west part of the field. This section describes the improvements made to the model to obtain a closer match between model performance and actual field behaviour.

Improvements

The Groningen full field history match in general is of good quality. The typical pressure mismatch is in the order of only a few bars (RMS). However, in some of the peripheral areas of the field, where aquifers are connected to the field, discrepancies exist with respect to water encroachment into the field. As well density is often lower in these areas, observations of pressure and water rise can be scarce. Some of the discrepancies observed between modelled and measured subsidence can be traced back to the uncertainty in compaction in these areas, which in turn is related to porosity and pressure uncertainties. In the 2013 winningsplan, two different models G1 and G2 were therefore used.

- The focus for the G1 model has been to obtain an improved compaction/subsidence match in the Loppersum Area; and match for pressure and water encroachment in the south-west peripheral area was compromised
- The G2 model resulted in a good reservoir pressure history match, but the subsidence match was compromised

Attempts to build a single model to match all observations were not successful. The history match for both the G1 and G2 models showed discrepancies in the Eemskanaal (Figure 8) and Harkstede areas. In particular the production from the only well producing from the Harkstede block, Eemskanaal-13, was poorly matched (Figure 9 and Figure 10).

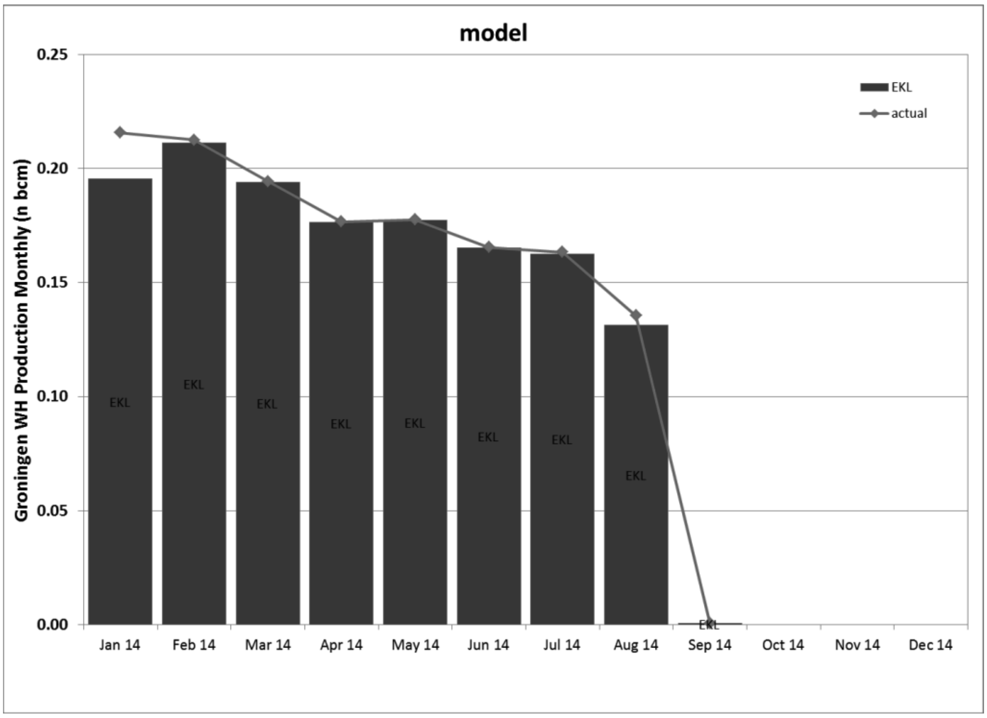


Figure 8 *Production from the Eemskanaal Cluster (wells EKL-1 to EKL-12, i.e. excluding EKL13) model (G1) results compared to actual production for January to September 2014. In September 2014 these wells did not produce because of a planned three-yearly maintenance and inspection shutdown.*

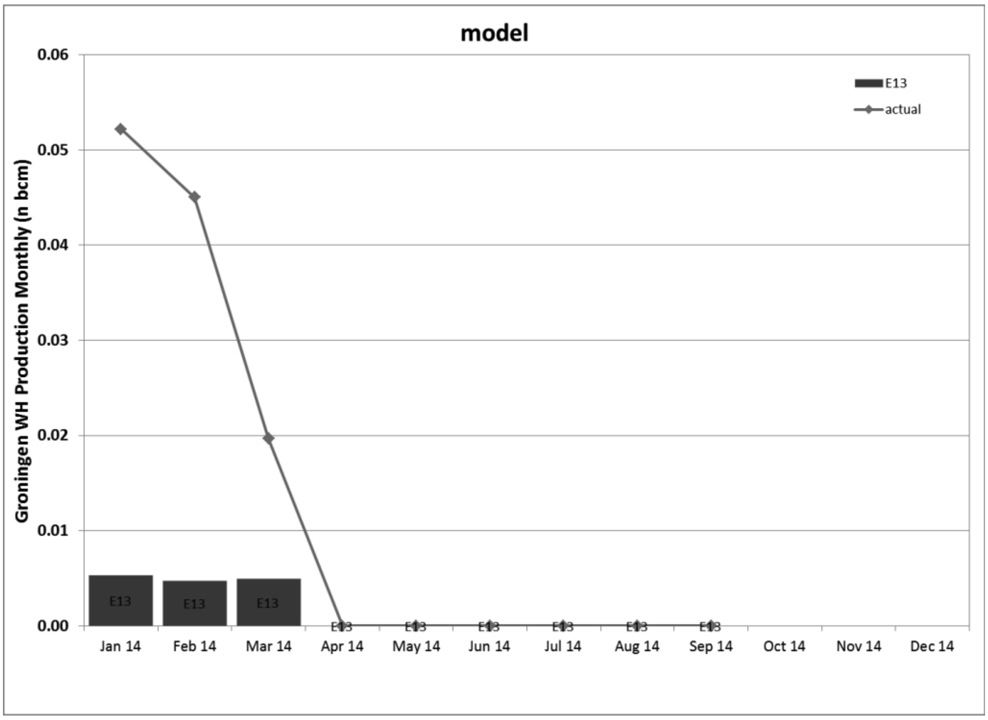


Figure 9 *The production from well EKL-13 producing from the Harkstede block, comparison between model results and actual production. Due to excessive water production in the model, the well suffers from lift die-out and is not able to produce gas. In reality, the well has produced gas during the first three months of 2014. The well has been closed-in since April.*

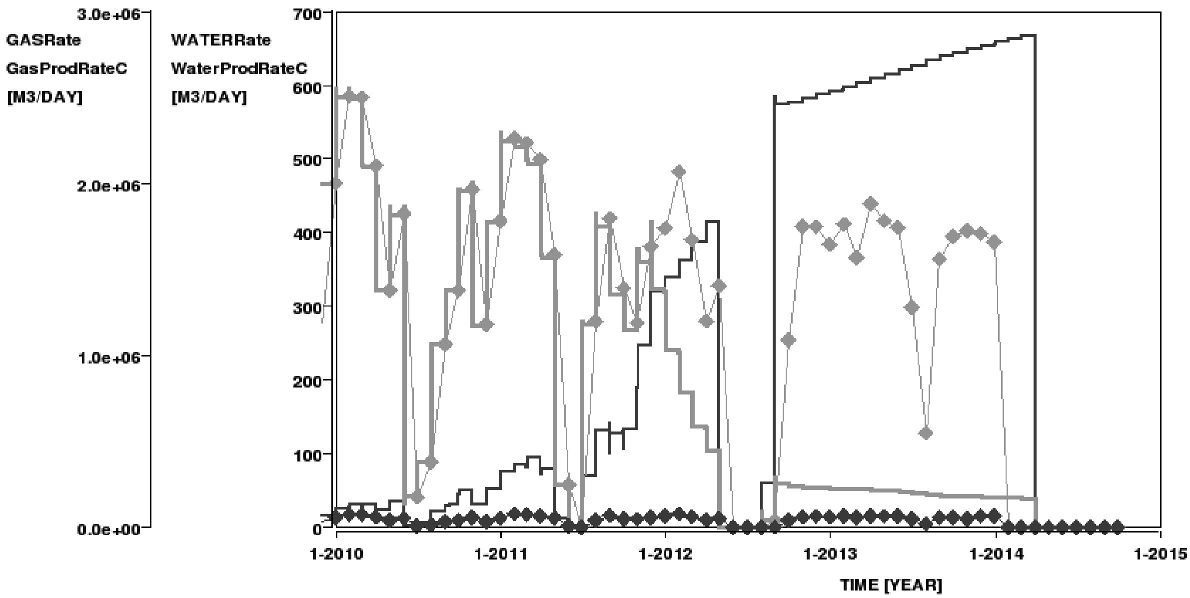


Figure 10 Production from EKL-13, The excessive water production from this well in the G1 model causes the well to stop production due to lift die-out. Dots are production data and the lines are G1 model results.

This poor match between field performance observations and modelling results is most likely related to the uncertainties in the geological model of that peripheral part of the Groningen field. These uncertainties are described below.

Static Model

The poor match between observations and modelling results is most likely related to the uncertainties in the geological model of the peripheral part of the Groningen field. A better match can probably be obtained with an increased static volume in the Harkstede block compared to base case static model. This is a feasible option if such an increase can be realized within the uncertainties of the dominant input parameters, i.e. bulk rock volume and porosity. These uncertainties are evaluated in the following.

<u>Porosity uncertainty</u>

Maps 1 to 4 in figures 11 and 12 show the average porosity per reservoir zone in the south-west periphery of the Groningen field. The maps are derived from up-scaled wireline log measurements from wells in the area, which are interpolated using a convergent gridding algorithm. The average porosity in the Harkstede block ranges from approximately 14 to 15.5%. These values are consistent with the observed values for neighboring wells in the area. The relative uncertainty as reported in the GFR2012 Field Review document is 0.022 (= 1 SD). This means that the maximum porosity in the Harkstede block could be as high as 16.2% (= 15.5 + 2 SD).

Map 1: USS.3res Map 2: USS.2res

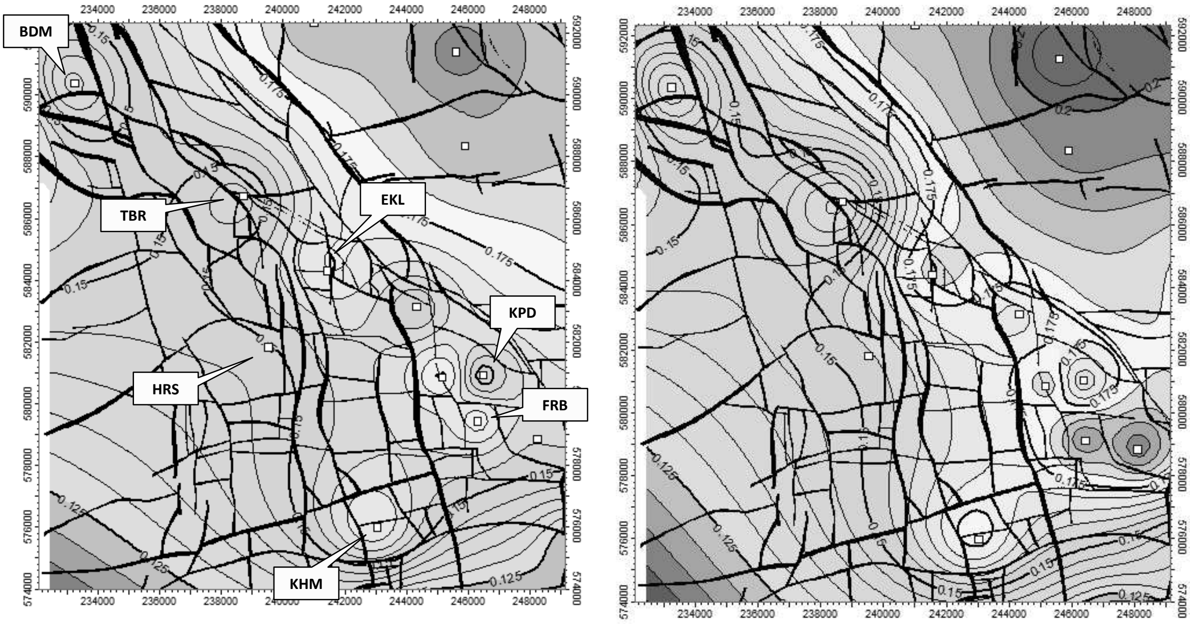


Figure 11 Porosity [faction] for the Upper Slochteren Sandstone Formation is shown for reservoir layers 2 and 3.

Map 3: USS.1res Map 4: LSS.2res

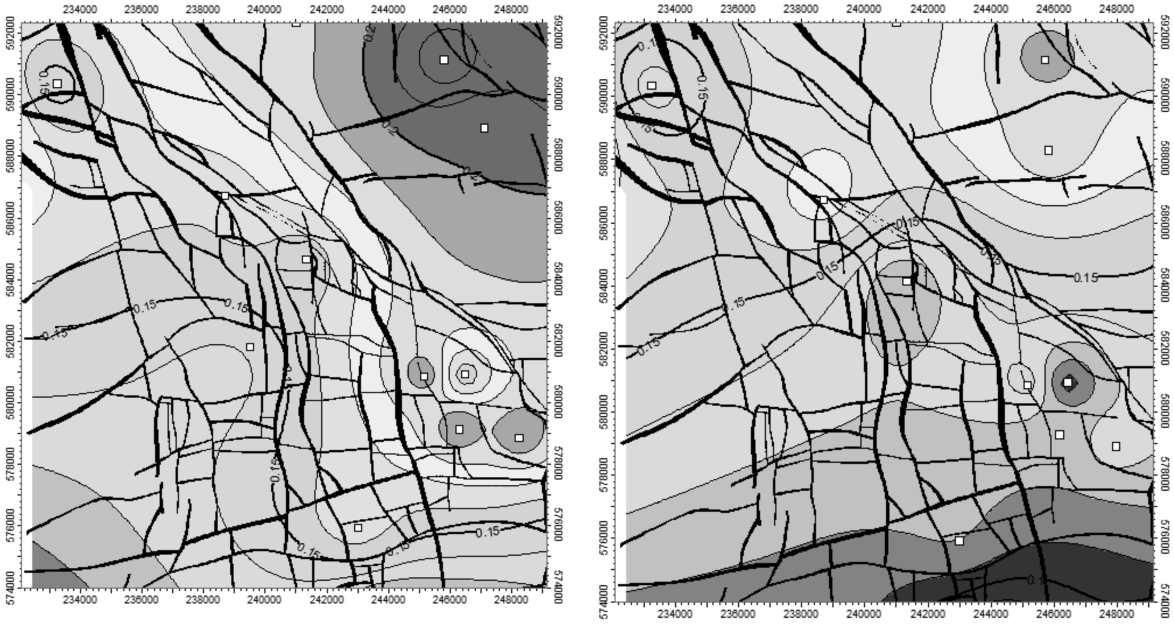


Figure 12 Porosity [faction] for the Upper Slochteren Sandstone Formation reservoir layer1 and the Lower Slochteren Formation reservoir layers 2.

<u>Top map uncertainty</u>

Figure 13 shows a structural map of the Top Rotliegend horizon in the South-West periphery. The method for establishing the uncertainty in this map is described in the same GFR2012 document, and is presented as a 1 SD uncertainty map. Figure 14 shows this uncertainty map zoomed in for the

Harkstede area. Uncertainties at the well locations (EKL-13, HRS-1 and HRS-2A) are (close to) zero. Away from these well control points, the uncertainty in the block grows to a maximum of 22 m. The average uncertainty for the whole block will be slightly over 10 m.

Map 5: Top_Rotliegend structural map of the Groningen SW Periphery

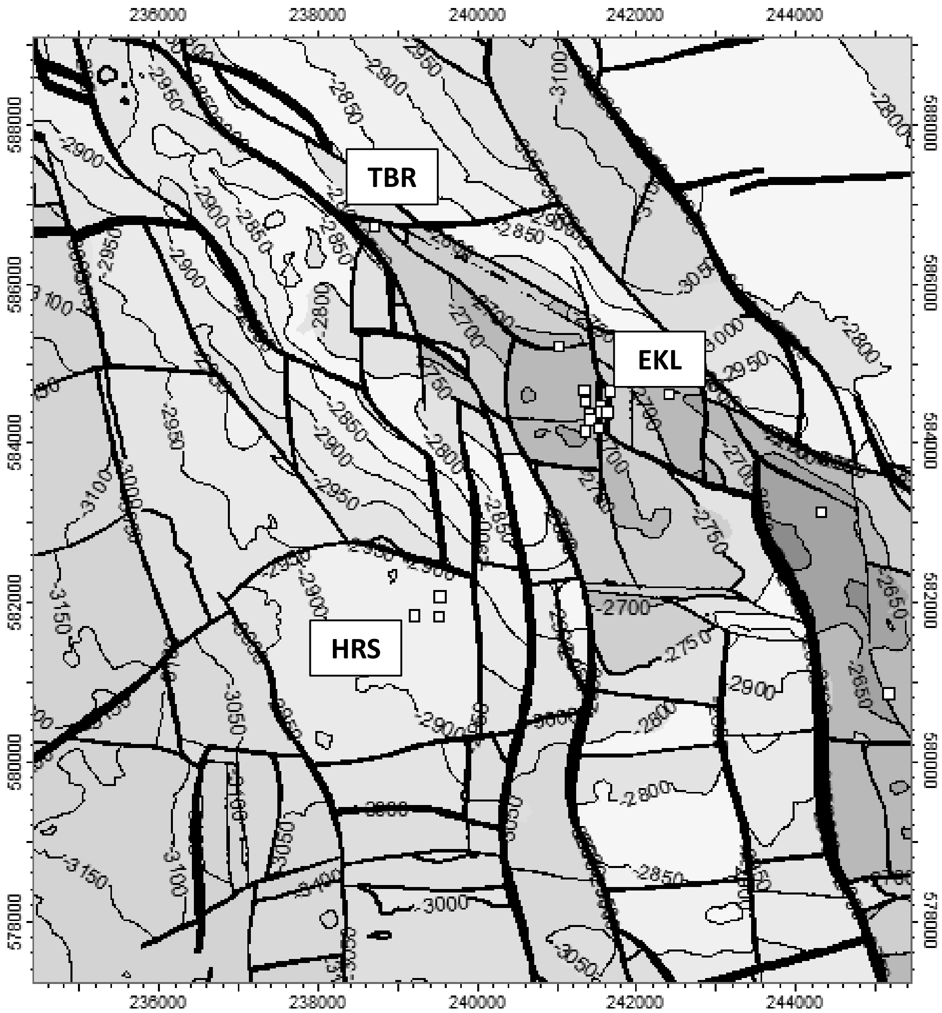


Figure 13 Structural map of the Top Rotliegend horizon in the SW periphery.

Map 6: Depth uncertainty map for the Groningen SW Periphery

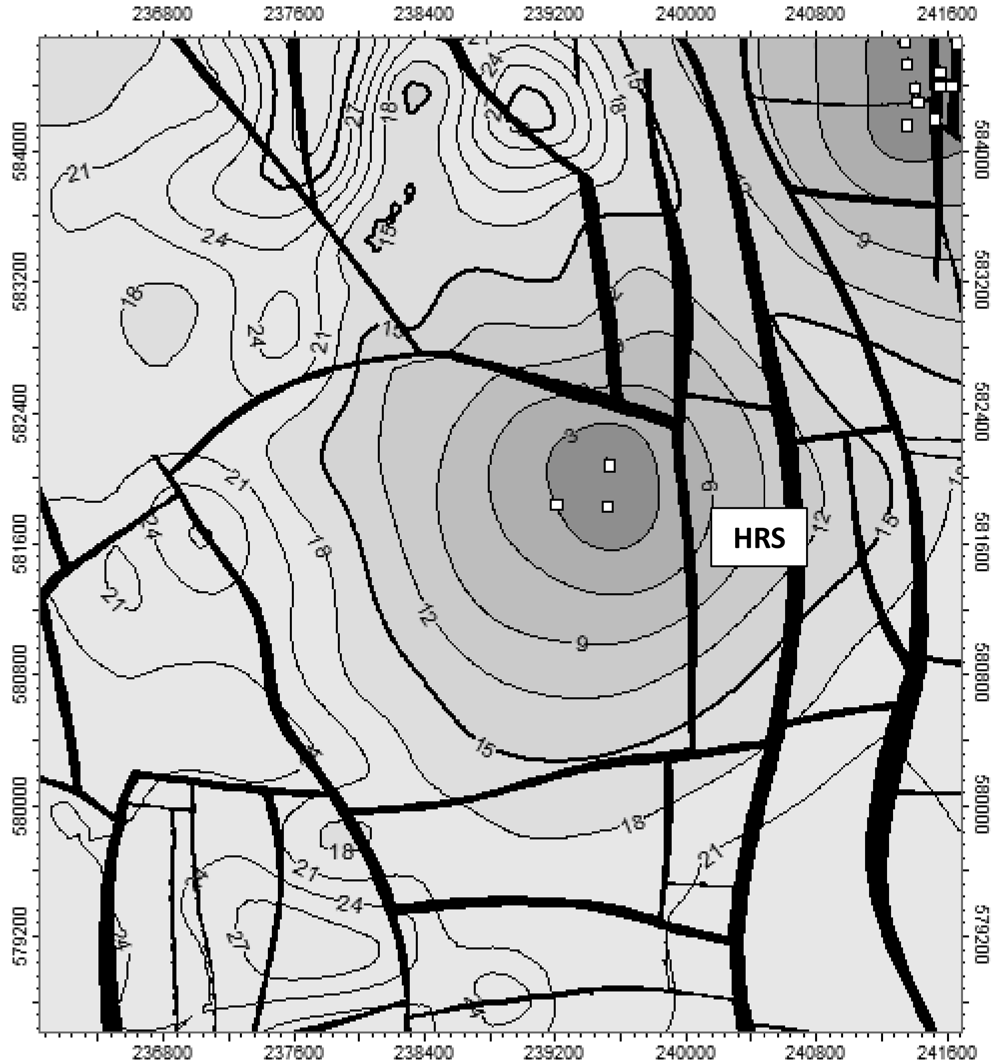


Figure 14 The uncertainty map zoomed in for the Harkstede area.

Based on this assessment of the uncertainties in the geological data, it was concluded that the porosity in the Harkstede block is unlikely to be more than 1.5 % higher than in the reservoir model, while the uncertainty in the top of the reservoir could increase away from the Eemskanaal-13 well and the Harkstede-1 well to some 20 meters. The limit of the uncertainty in porosity was therefore set at + 1.5% and for top reservoir top at 10 meters average for the block.

Dynamic Model

Two different history matched models will be used in this Eemskanaal hazard assessment. Both models are based on the G1 model used for the hazard assessment in the Winningsplan 2013, and are here referred to as Models 1 (STR40) and 2 (STR38). With both models, a good match is obtained for all wells of the Eemskanaal Cluster including EKL-13 in the Harkstede block (Figures 15 and 16). Together, these two models capture the inherent volumetric uncertainty in the static reservoir model.

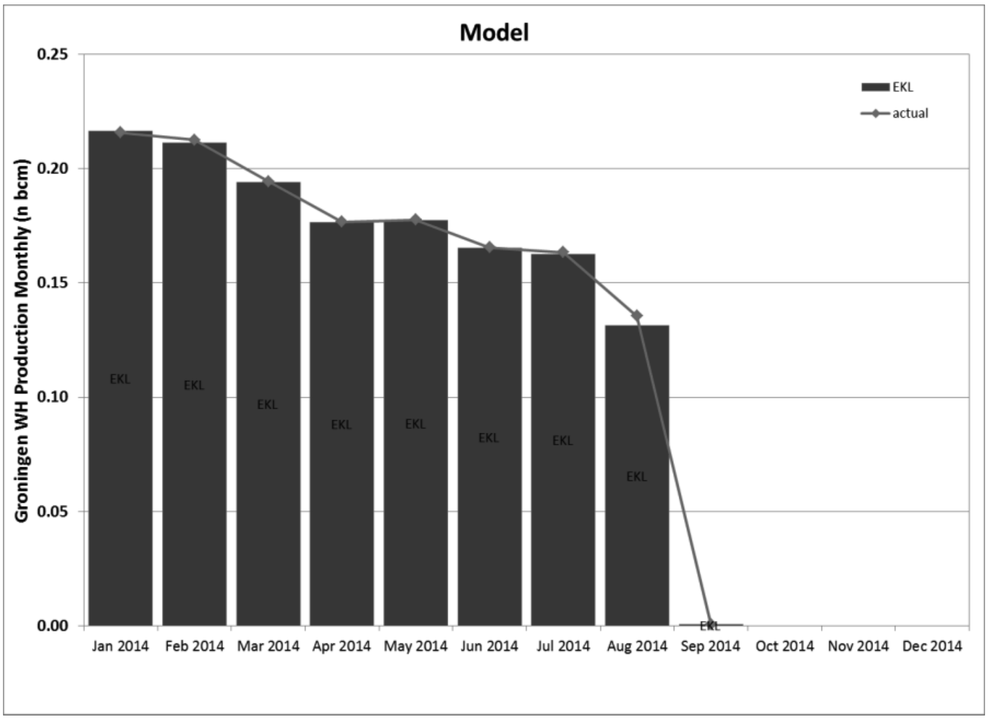


Figure 15 *Modelled and actual production from the Eemskanaal Area (wells EKL-1 to EKL12, i.e. excluding EKL13, improved G1 model) for the period January to September 2014. In September 2014 these wells did not produce because of a planned three-yearly maintenance and inspection shutdown.*

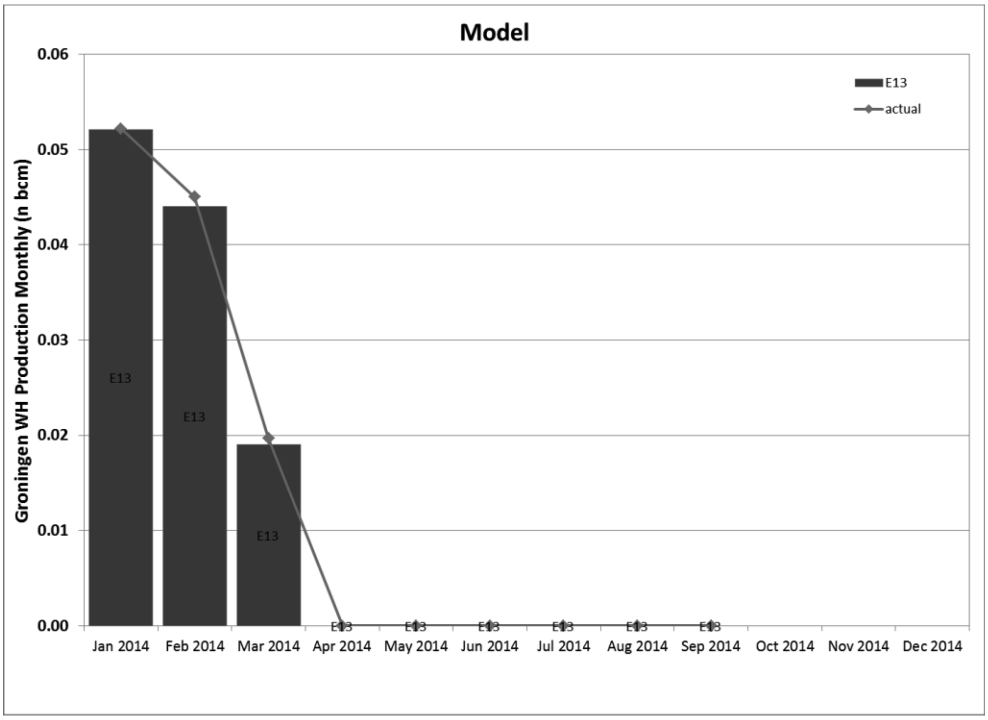


Figure 16 *Modelled and actual production from well EKL-13 in the Harkstede block, (improved G1 model). EKL-13 is the only well producing from the Harkstede block. The well has been closed-in since April.*

Model 1 [Model 40]

In Model 1, the following changes have been made to the G1 model,:

- Harkstede block structure on average 10 meters shallower,
- Porosity in the Harkstede block is increased by 1.5%,
- Permeability in the Harkstede Noord block is increased,
- Permeability in the aquifer in the South West periphery is reduced and
- The transmissibility of two faults in the South West periphery is reduced.

A complete rebuild of the structural model was not feasible within the time frame for this evaluation. Therefore, the shallower structure was approximated by a local lowering of the GWC with 10 m.

With these changes to the G1 model, an improved history match for the Harkstede block was achieved. Well Eemskanaal-13 in the original G1 model stopped producing due to lift die-out. In the new Model 1, the same well was able to produce the observed gas production volumes. A very good match between observed and modelled reservoir pressure was obtained for all wells of the Eemskanaal cluster. The pressure match for the two wells located in the Harkstede block is in model 1 also good (Figures 17 and 18).

Water production from the Eemskanaal-13 well in Model 1 is reduced compared to the original G1 model. The well produced about 12 m^3/day formation water over the last 5 years (WGR is approximately double that of condensed water alone) and Model 1 shows a water rate of about 3 m^3/day, see Figure 19. Note that condensed water is not modelled explicitly by the models.

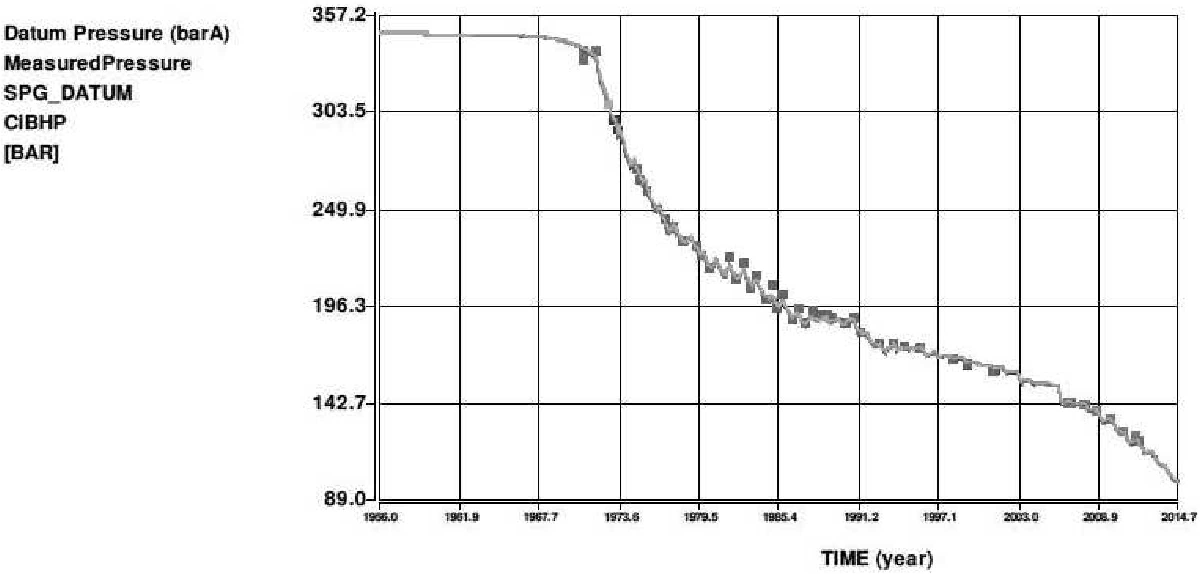


Figure 17 Model 1: Pressure match for the wells producing from the Eemskanaal Area (EKL-1 to EKL-12).

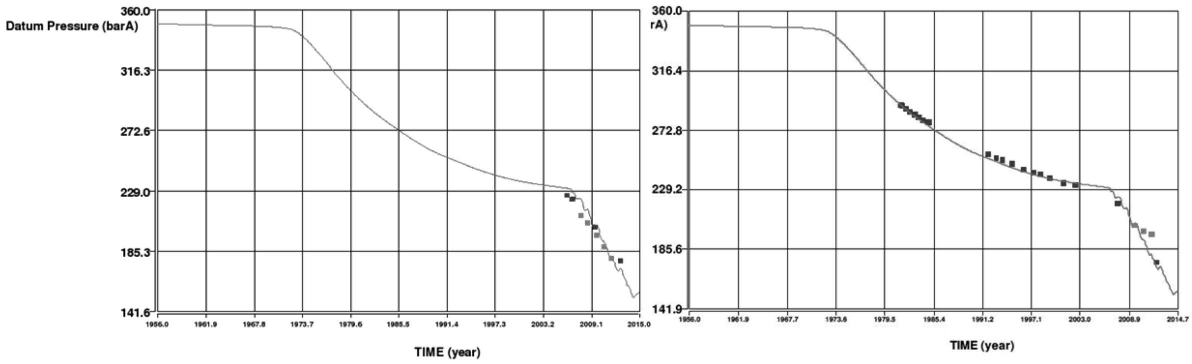


Figure 18 *Model 1: Pressure match for the two wells located in the Harkstede block. Left: Producing well EKL-13 and Right: Observation well HRS-2A. The blue squares are high-confidence SPTG pressure data and the pink squares are lower-confidence reservoirs pressures calculated from closed-in THP data.*

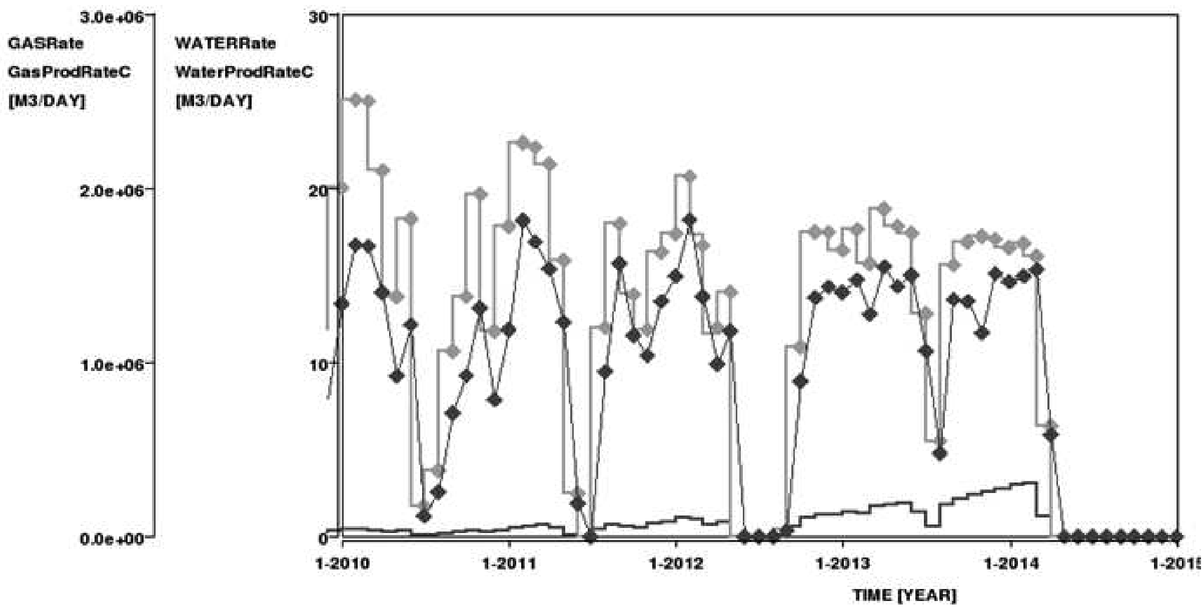


Figure 19a *Model 1: Production Match for EKL-13 for Model 1. The excessive formation water production from the G1 model has been reduced in Model 1. The connected dots are production data and the lines are the model results. Note that the condensed water is not explicitly modelled and that condensed water has a WGR of about 6 m^3/mln m^3 at the current field conditions.*

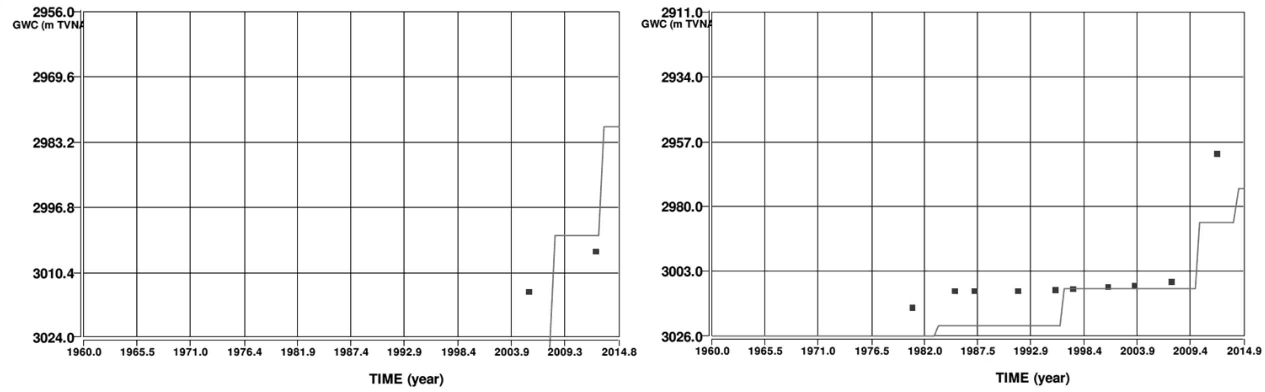


Figure 19b Model 1: Water rise seen in the wells in the Harkstede block. Comparison of measured observations (PNL logs) and model results. Left well is Eemskanaal-13, well Harkstede-2A to the right.

Model 2 [Model 38]

An alternative model was prepared to further evaluate the impact of the sub-surface uncertainty. This Model 2 is also based on the G1 model from the 2013 winningsplan. The same changes were applied as for Model 1, with the addition that the aquifers west of the Harkstede block and Eemskanaal area (the so-called Lauwerszee A and B aquifers) were assumed to be very poorly connected to the gas reservoir.

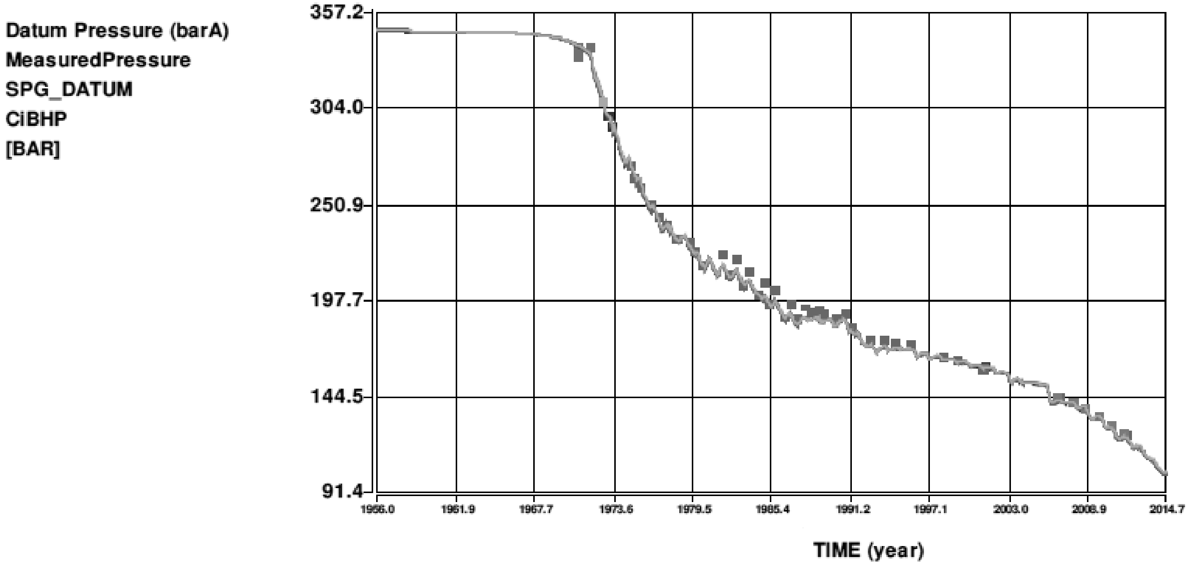


Figure 20 Model 2: Pressure match for the wells producing from the Eemskanaal Area (EKL-1 to EKL-12).

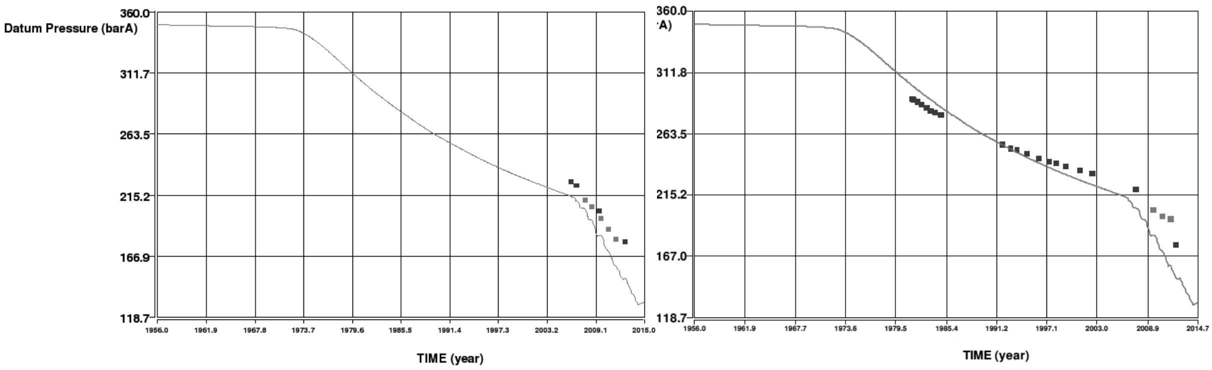


Figure 21 Model 2: Pressure match for the two wells located in the Hartstede block. Right: Producing well EKL-13 and Right: Observation well HRK-1.

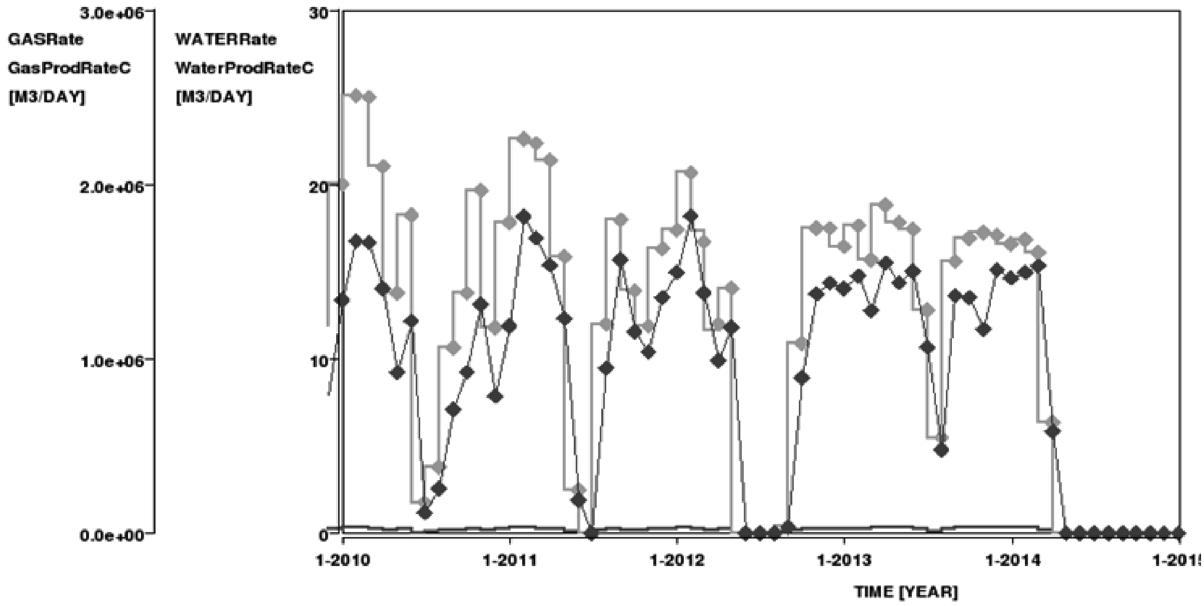


Figure 22 Model 2: Production Match for EKL-13. The excessive water production from the G1 model has been reduced in Model 2. The connected dots are production data and the lines are the model results. Note that the condensed water is not explicitly modelled and that condensed water has a WGR of about 6 m^3/mln m^3 at the current field conditions.

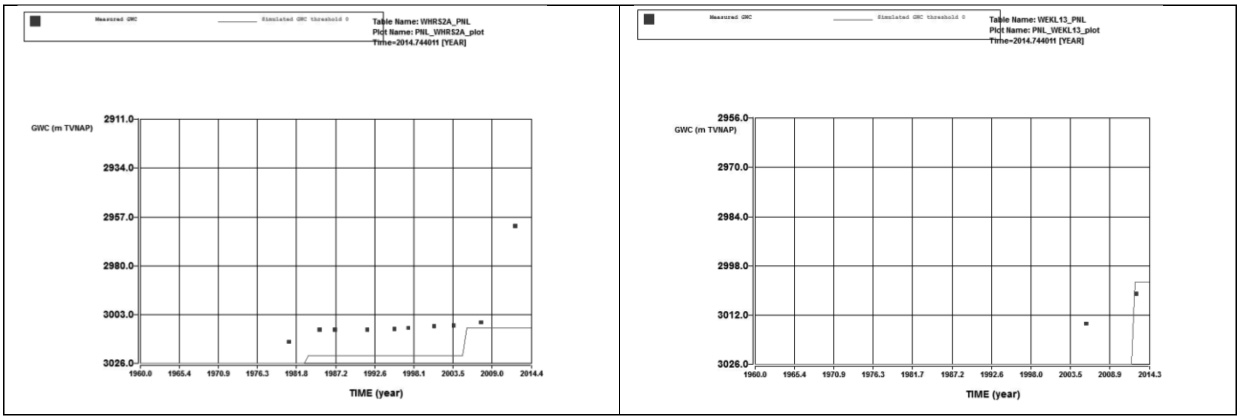


Figure 23 Model 2: Water rise seen in the wells in the Harkstede block. Comparison of measured observations and modelling results. Left well Harkstede-2A and Right Eemsknaal-13

In general, the performance of Model 1 is similar to Model 2. The history match quality for the two wells in the Harkstede block is slightly poorer. Model 2 predicts a lower reservoir pressure for both wells than actually observed for this block. The difference is in the order of 10 bar.

The reservoir pressure distribution in 2014 of the two models for the Eemskanaal area is shown in figure 24.

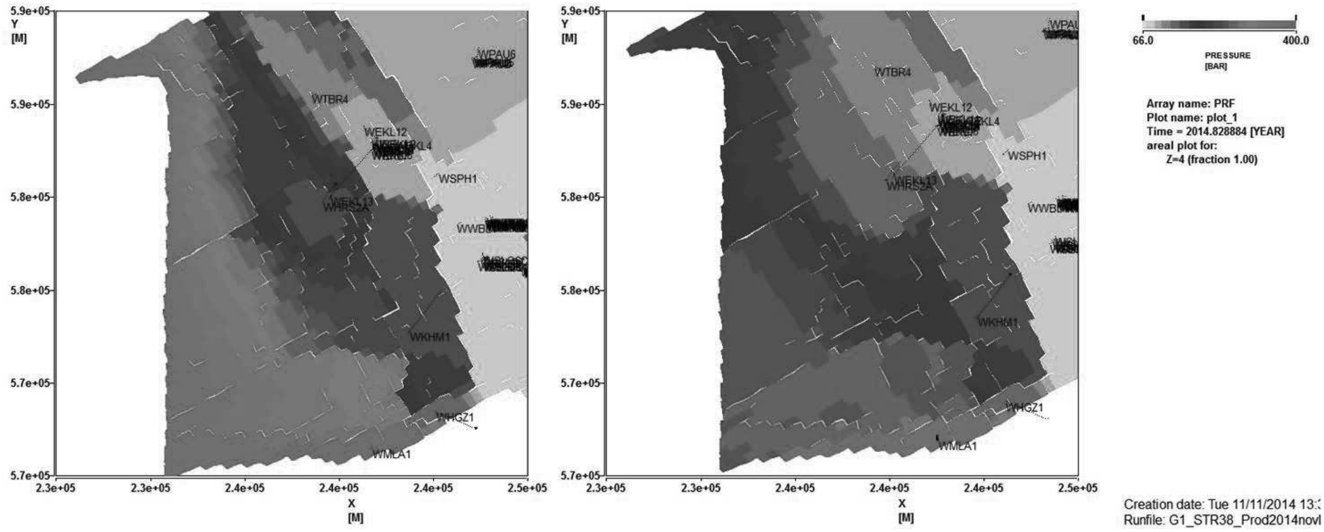


Figure 24 Pressure map of upper Slochteren reservoir for Oct 2014. Left: model 1 with the Lauwerszee A&B aquifers on the western edge (higher pressures) and Right: model 2

Conclusion

The Groningen reservoir model G1 was updated with an improved match (historical) to better predict (future) production and pressures in the Harkstede area and EKL cluster area. This resulted in two different reservoir scenarios; Model 1 [40] with the same Lauwerszee aquifers as for the G1 model and model 2 [38] with a very poor connection to the Lauwerszee aquifers on the South-Western edge of the model. Both models result in an acceptable match to the historical reservoir pressures and gas production. In this note the effects of these changes on the geomechanical modelling are discussed.

Subsidence and compaction in the Eemskanaal

The results of the improved history matched models as described in the previous section have been used to make new compaction and subsidence calculations. These were carried out with both the Time-decay and the RTCiM compaction models. As the reservoir pressure updates are relatively minor, the geomechanical parameters used for the Time-decay compaction model were copied from the model used in the Winningsplan (2013). The RTCiM parameters were taken from the TNO report (Ref. 3).

The main parameters used in the Time-decay compaction model are:

Cm factor: 0.45

Decay time: 7.3 year

For the RTCiM compaction model:

Cm factor α = 0.57 [-]

Cm,a/Cm,ref = 0.44 [-]

b = 0.017 [-]

The goodness of fit is checked by means of an RMS calculation. The RMS is defined as

$$RMS = \sqrt{\frac{\sum(Measured - Model)^2}{n}}$$

Subsidence measurements were used as reported in the state of differences 000A2080_1964-01-01_NN2013.csv, which is the “Concept State of differences ” (differentie staat) reported to SodM (van Lieshout dd 29 Oct 2014).

For this calculation all stable benchmarks, as defined in the state of differences , were used. The RMS was calculated using each benchmark and each epoch starting with the first measurement of this benchmark.

The epochs used in the RMS calculations are

H_15_04_1964	D_10_12_1994	D_10_12_2005
H_01_09_1972	D_11_12_1995	D_10_12_2006
H_01_09_1975	D_10_12_1996	D_11_12_2007
H_15_07_1978	H_13_06_1997	H_13_08_2008
H_01_07_1981	D_10_12_1997	D_10_12_2008
H_01_09_1985	H_05_06_1998	D_10_12_2009
H_01_08_1987	D_10_12_1998	D_10_12_2010
H_15_05_1990	D_11_12_1999	D_11_12_2011
H_14_05_1991	D_10_12_2000	D_10_12_2012
D_10_12_1992	H_17_06_2003	H_25_04_2013
H_28_06_1993	D_11_12_2003	
D_10_12_1993	D_10_12_2004	

Table 1 Epochs available in the state of differences

An epoch name starting with an H indicates a leveling survey and a period starting with a D indicates an InSAR survey.

The benchmarks used in the RMS calculation are selected from the South-West area of the Groningen field, i.e. the area of the Eemskanaal cluster (Figure 24) (see section Subsidence Observations).

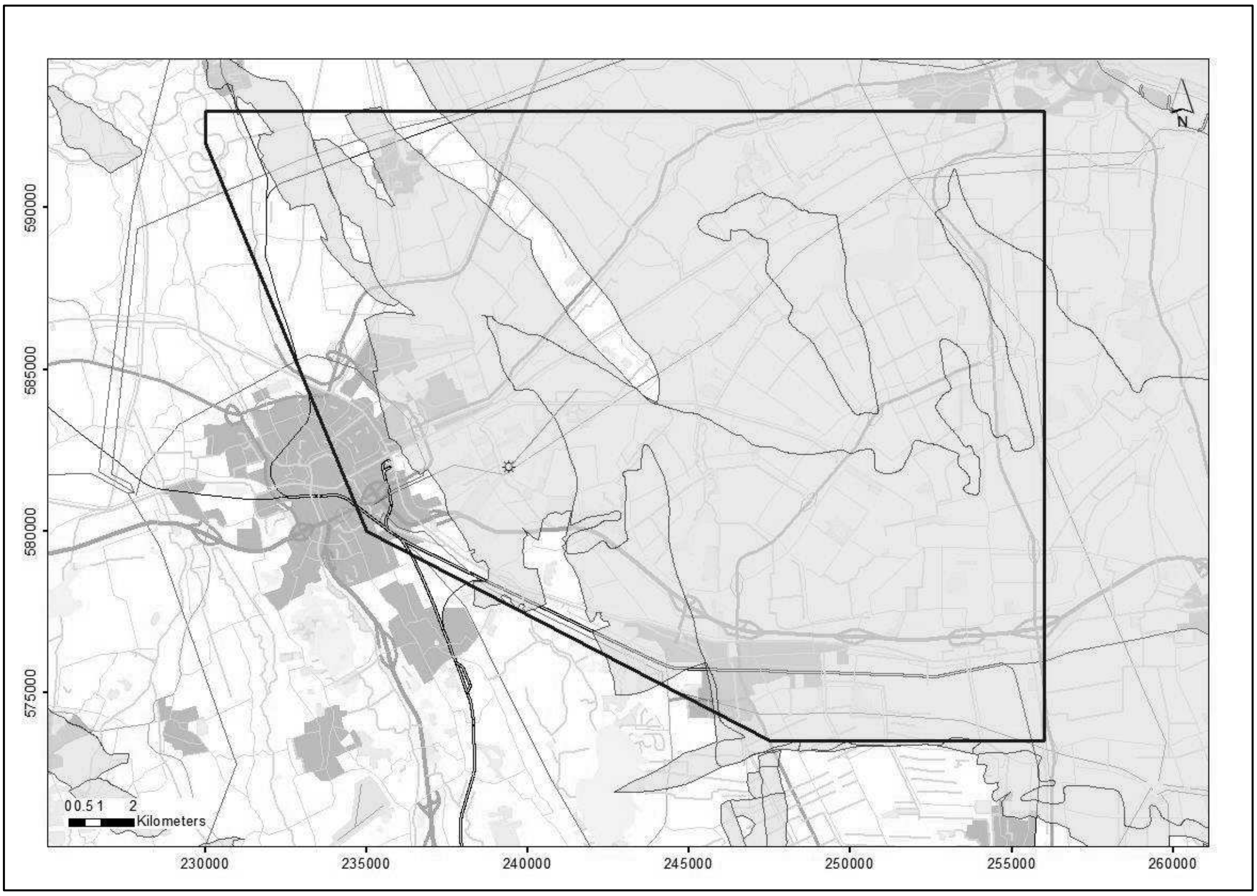


Figure 24 Area of interest (purple polygon). The gray line indicates the EKL-13 well trajectory, with the round symbol, indicating the location of the well at reservoir level.

Subsidence calibration

The first step is to calculate subsidence based on the G1 model used in de Winningsplan 2013. This is done for both the Time-decay and RTCiM compaction models for the period 1972 – 2012 and shown in Figure 25. This period was chosen because only limited data (fewer benchmarks) is available for the period from 1964 to 1972.

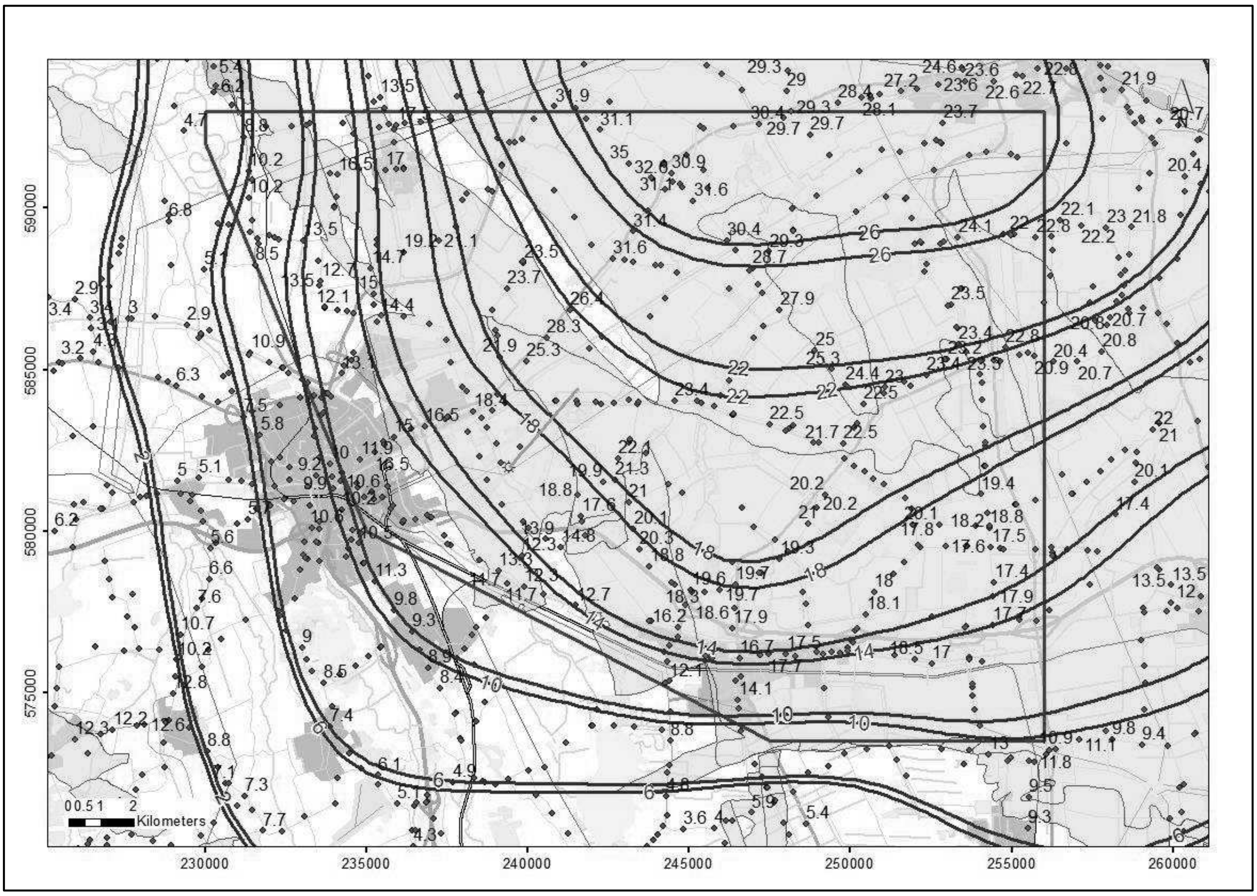


Figure 25 Measured (points) and modelled subsidence (contours) in cm. The blue contour represents the subsidence derived from the Time-decay compaction model, the red contour represents the subsidence derived from the RTCiM compaction model. Measurements and modelled contours are for the period 1972-2012. The purple polygon shows the area in which the benchmarks were selected for the RMS calculation.

In the South-West corner of the map in Figure 25, a part of the Roden field can be seen. Here, the observed subsidence deviates from the subsidence modelled with the Groningen model, due to the impact of production from the fields in the Drenthe-East Friesland area. The RMS values in the area of interest for different compaction models are shown in Table 2.

Compaction model	RMS
Time-decay	1.53
RTCiM	1.66

Table 2 RMS values using the Time-decay and RTCiM compaction model for the Winningsplan model.

Scenarios

The subsidence modelling results based on the Winningsplan 2013 G1 model (previous section) have to be compared with calculations based on the updated reservoir models 38 and 40. Table 3 lists the scenarios evaluated for this purpose.

EKL scenario	EKL production (mln m^3 /d)	Reservoir model	Compaction model
M0	G1 (Winningsplan 2013)		Time-decay and RTCiM
M3	3	Model 1 (STR 40) (strong aqf) Model 2 (STR 38) (weak aqf)	
M4	5		
M5	8		

Table 3 Scenarios used for compaction modelling

In the graphs these scenarios are indicated with acronyms, i.e. M3STR40TD_14 means EKL scenario 3 (M3), reservoir model STR40, compaction model Time-decay (TD), calculated for the year 2014 (14).

Modelling Eemskanaal

A comparison between the measured subsidence between 1972 and 2012, the modelled subsidence for the G1 model (winningsplan 2013) and the two reservoir models (STR 38 and STR 40) using the Time-decay compaction model is shown in Figure 26. Only the stable benchmarks as reported in the state of differences are shown.

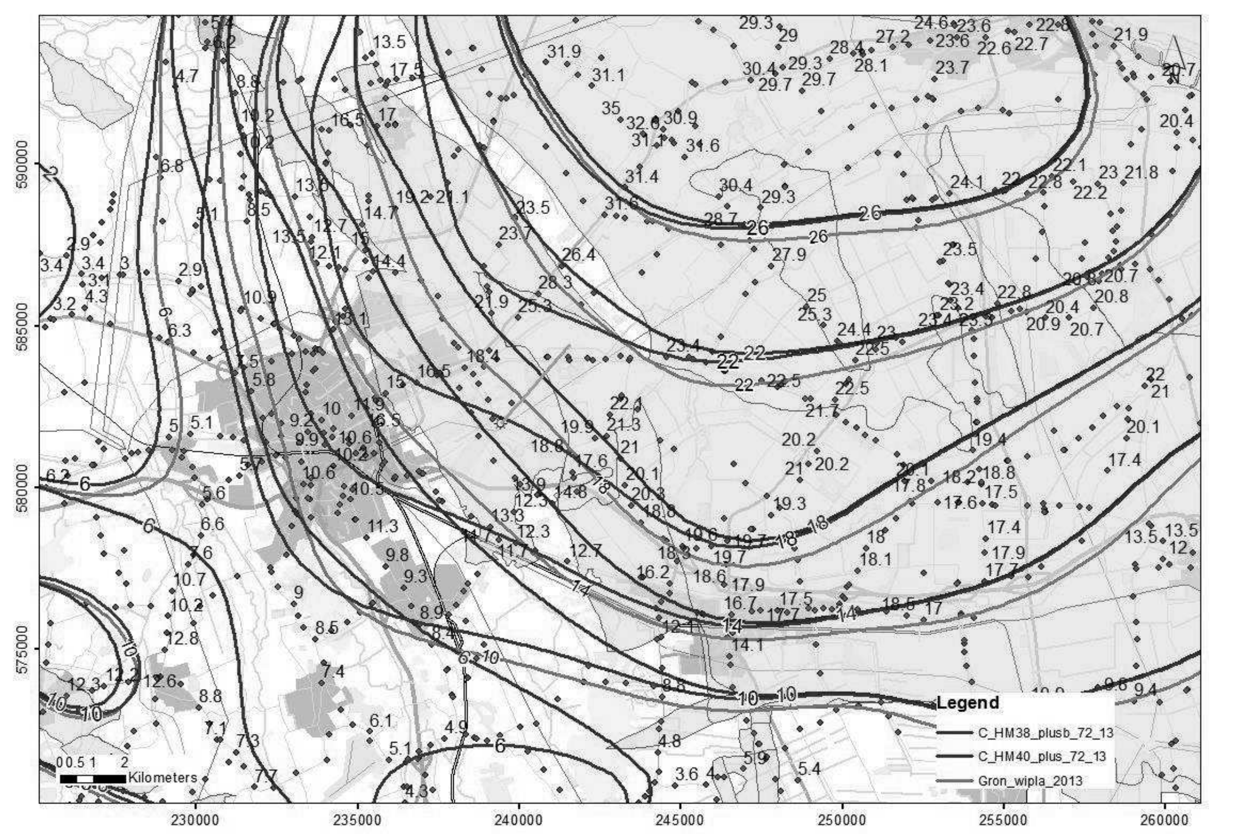


Figure 26 Measured (stable benchmarks) and modelled subsidence (contours) for the period 1972-2012 for the three different reservoir models calculated for with the Time-decay compaction model. (subsidence in cm). The model used for the winningsplan 2013 (Green), Subsurface Model 1 [40] (Red) and Subsurface Model 2 [38] (Blue) are shown.

The scenario with the stronger aquifer (Model 1, STR40), i.e. less pressure depletion, shows the least subsidence. In general, modelled subsidence for this model is slightly smaller than measured subsidence. In the scenario with the weaker aquifer (Model 2, STR38), i.e. more pressure depletion, slightly more subsidence is modelled than measured. The subsidence calculated with the Winningsplan 2013 model is intermediate between these scenarios. The RMS values for the different models, calculated for the Time-decay model, are comparable (*Table* 4). The used of subsurface Models 1 (STR40) and Model 2 (STR38) captures the uncertainty in the subsidence, resulting from the uncertainty in the sub-surface model in the Eemskanaal and Groningen City Areas at the South-West periphery of the field.

Model (time-decay)	RMS
Winningsplan	1.53
Model 1 (STR 40)	1.58
Model 2 (STR 38)	1.67

Table 4 RMS values for the different models

Results of Compaction modelling

Figure 27 shows the total compaction volume for the two aquifer models and the G1 Winningsplan model for both the Time-decay and RTCiM compaction model. The RTCiM model shows slightly less compaction than the Time-decay model, which is in line with the finding that the RTCiM model results in less subsidence than the Time-decay model. The RTCiM compaction reacts faster on changes in the rate of pressure reduction caused by the higher production rate since 2010 (Figure 28).

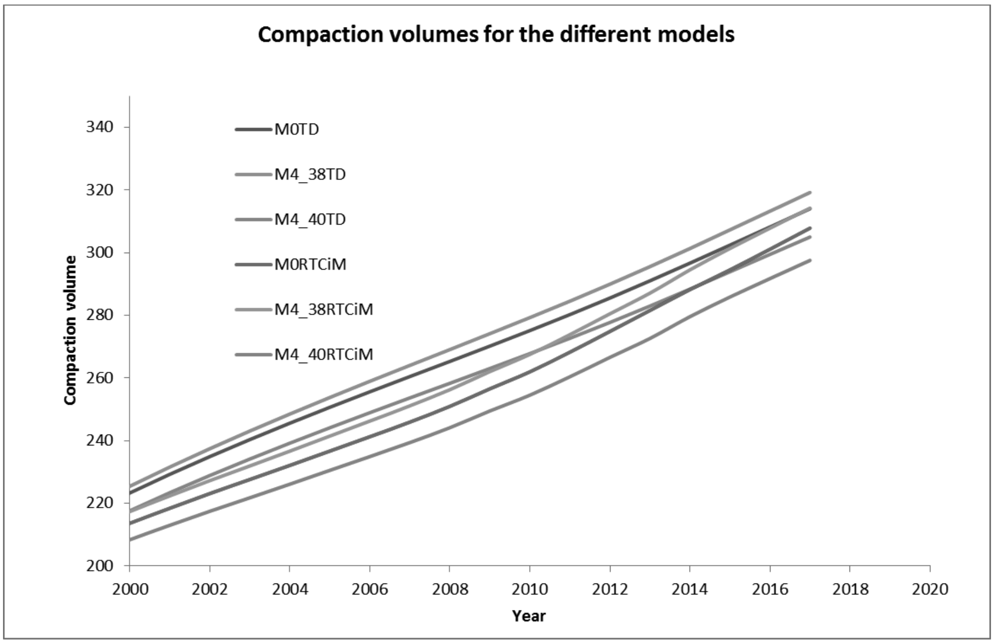


Figure 27 Total compaction volume for Winningsplan (Dark blue and Red, M0) and the two sub-surface models Model 1 (Green and Brown, 40) and Model 2 (Light blue and Purple, 38) for the EKL base case production of 8 mln m^3/day average, calculated with both the Time-decay (TD) and RTCiM compaction models.

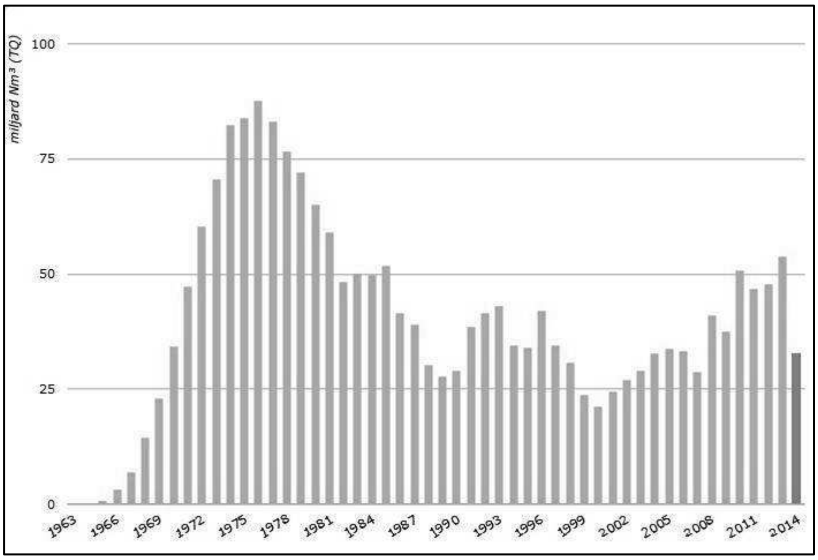


Figure 28 Yearly gas production of the Groningen field (2014 is YTD) (ref. NAMPLATFORM)

The compaction in the Eemskanaal area is calculated for both the Time-decay and RTCiM compaction model for the year 2014 (Figure 29 and Figure 30) and for the year 2017 (Figure 31 and Figure 32).

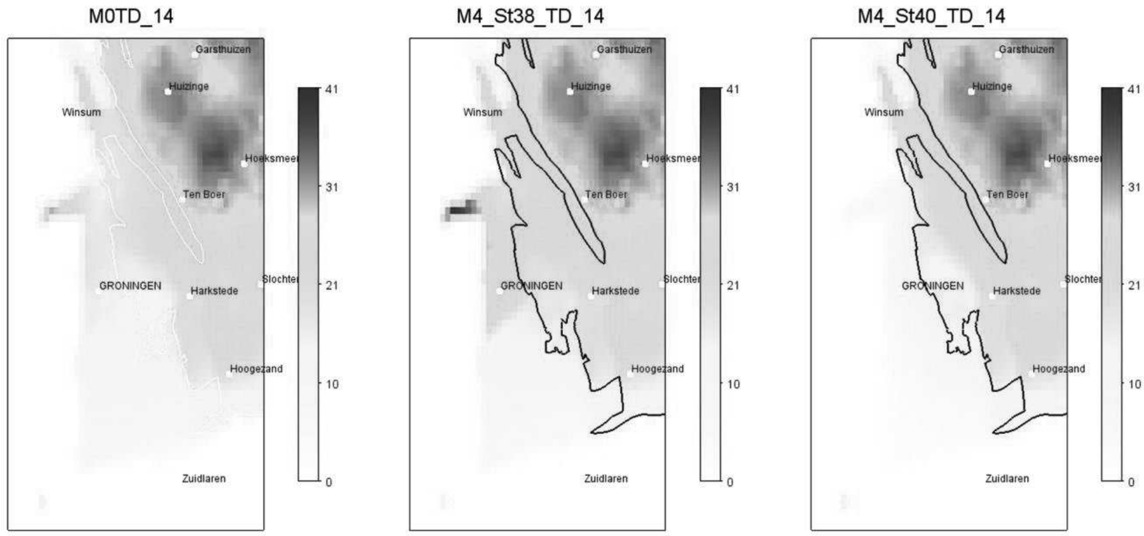


Figure 29; Compaction for the different models calculated with the Time-decay model for 2014, i.e. Winningsplan (M0), weak aquifer (STR38) and the stronger aquifer (STR40)

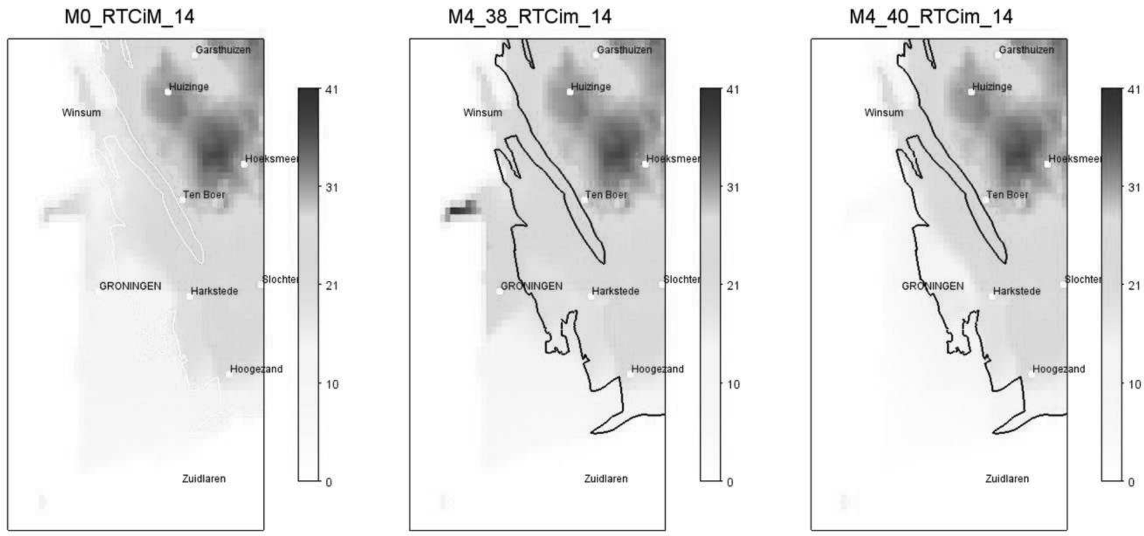


Figure 30 Compaction for the different models calculated with the RTCiM model for 2014, i.e. Winningsplan (M0), weak aquifer (STR38) and the stronger aquifer (STR40).

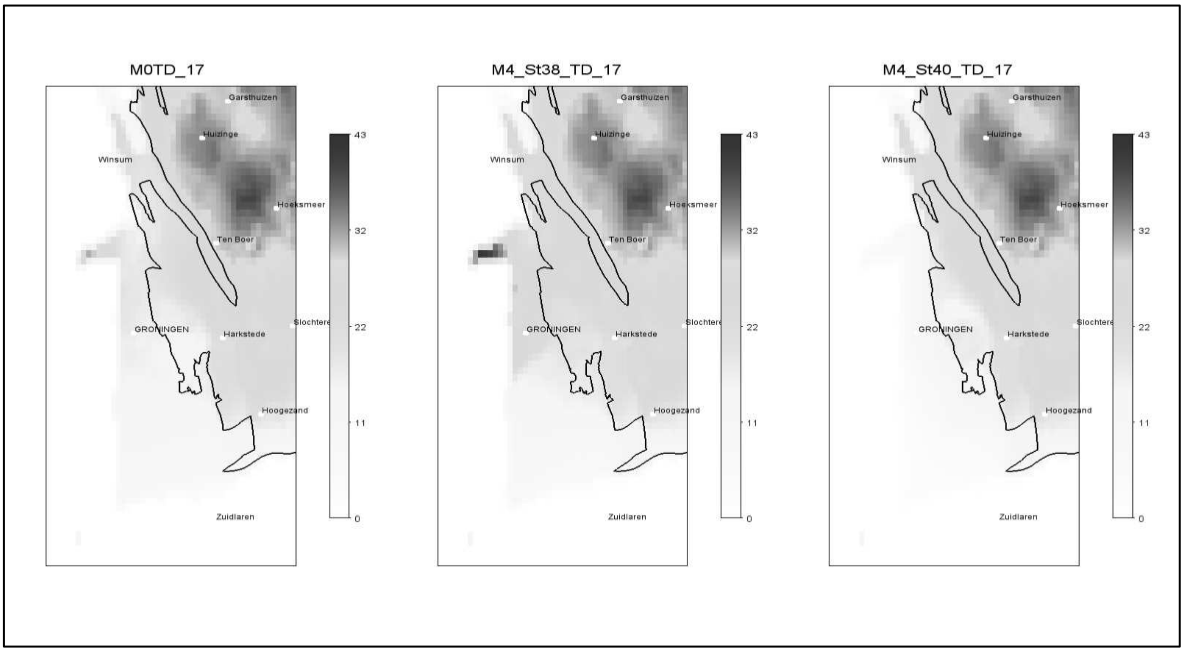


Figure 31 Compaction for the different models calculated with the Time Decay model for 2017, i.e. Winningsplan (M0), weak aquifer (M4, STR38) and the stronger aquifer (M4, STR40)

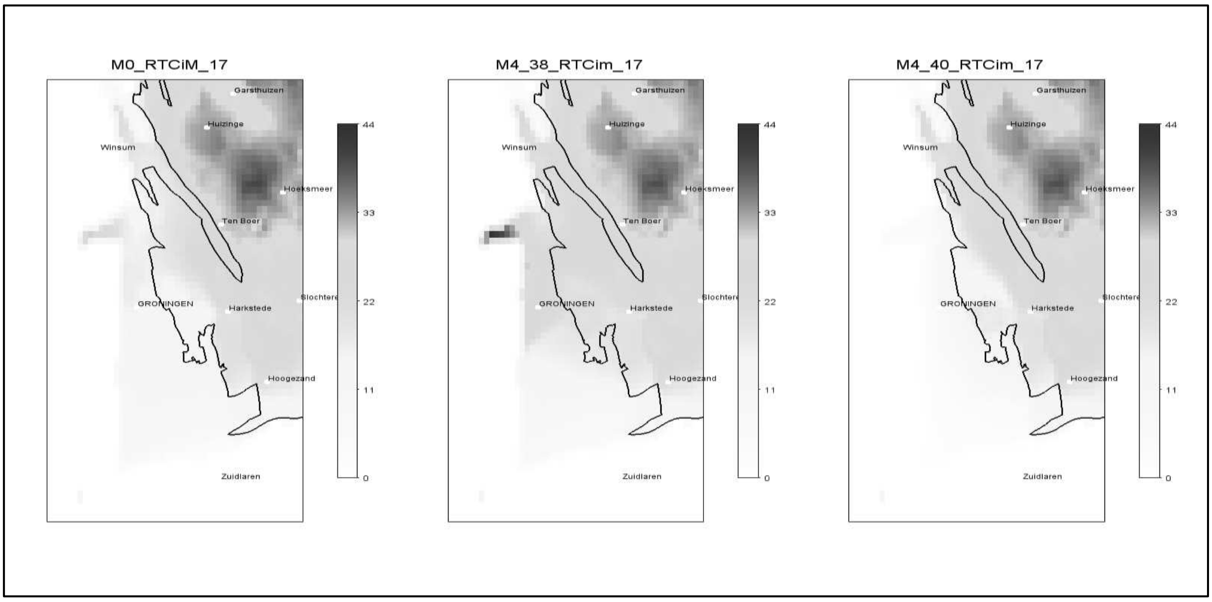
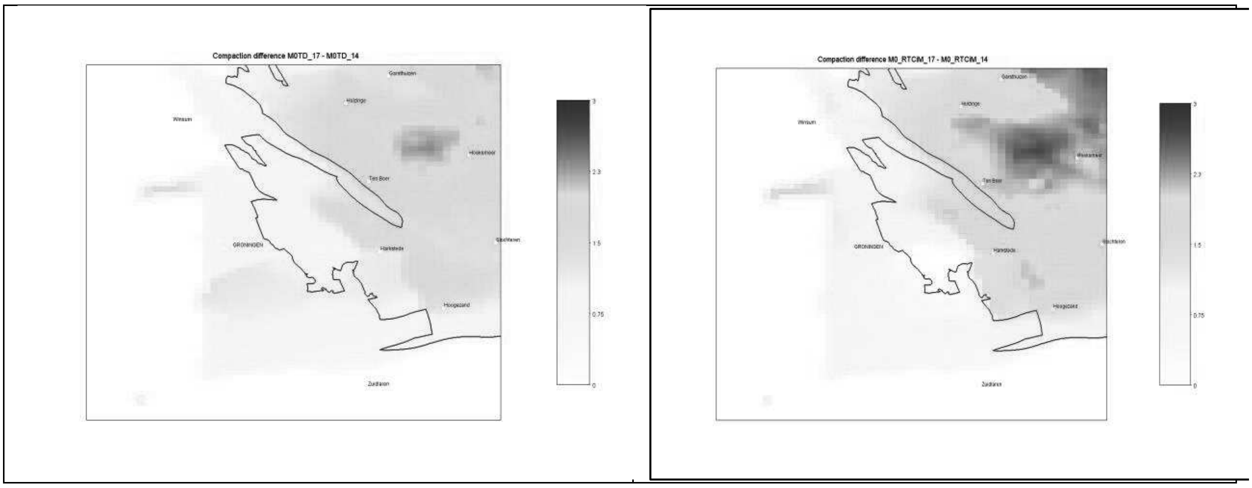


Figure 32 Compaction for the different models calculated with the RTCiM model for 2017, i.e. Winningsplan (M0), weak aquifer (M4, STR38) and the stronger aquifer (M4, STR40).

Compaction differences

The additional compaction in the 3 year period 1/1/2014 to 1/1/2017 for the G1 production senario (M0) for both the RTCiM and Time-decay compaction models is shown in Figure 33. The RTCiM model reacts faster to changes in production and the additional compaction is approximately one cm more than calculated with the Time-decay model. The additional compaction in this period for the three production scenarios and two reservoir models are shown in Figure 34 for the Time-decay compaction model and in Figure 35 for the RTCiM compaction model.



Time-decay RTCiM

Figure 33 Additional compaction for the G1 Winningsplan model (M0) between 2014 and 2017 for the Time Decay and RTCiM compaction model

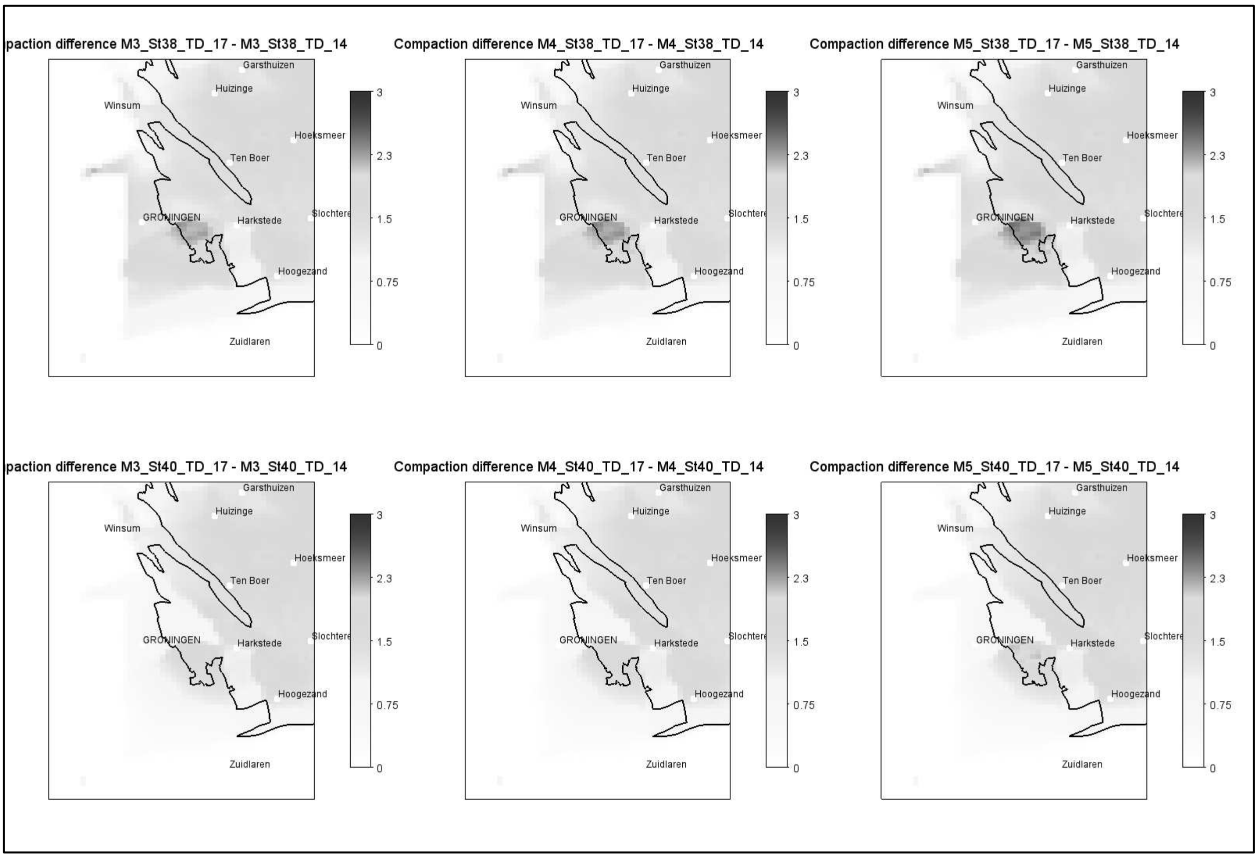


Figure 34 Compaction between 1/1/2014 and 1/1/2017 for the different reservoir models and production scenarios using the Time-decay compaction model. The left column shows the EKL production rate of 3 mln m^3/d (M3), the middle column 5 mln m^3/d (M4) and the right column 8 mln m^3/d (M5). The Top row shows the weak aquifer model (STR38) and the bottom row the stronger aquifer (STR40).

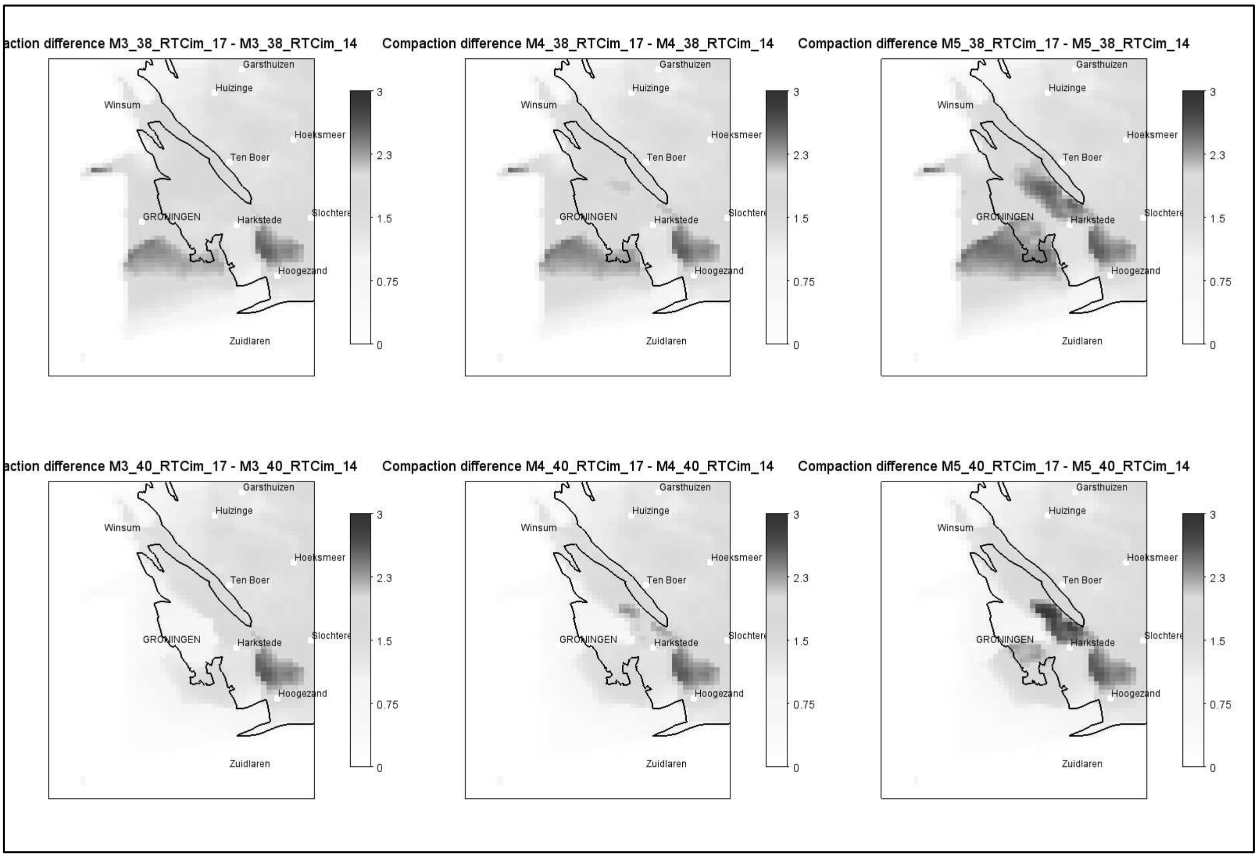


Figure 35 Compaction between 1/1/2014 and 1/1/2017 for the different reservoir models and production scenarios using the RTCiM compaction model. The left column shows the EKL production rate of 3 mln m^3/d (M3), the middle column 5 mln m^3/d (M4) and the right column 8 mln m^3/d (M5). The Top row shows the weak aquifer model (STR38) and the bottom row the stronger aquifer (STR40).

Seismic Response and Hazard

Methodology

Based on the compaction calculations an assessment of the hazard has been prepared for the period winningsplan period from 1/2014 to 1/2017. The uncertainty inherent in the hazard assessment has been assessed by a number of sensitivities.

To capture the uncertainty in the sub-surface three models are used; the G1 model used in the update of the winningsplan 2013, the enhanced model 1 (str40) and the enhanced model 2 (str38). The main difference between model 1 and model 2 is the assumption for the aquifers connected to the Groningen field to the west of the Eemskanaal area of the field (ref. section Dynamic Model). This represents the main uncertainty in the pressure distribution relevant for the hazard assessment.

Two alternative compaction models have been used; the Time-decay model developed in NAM (Ref. 1) and the RTCiM developed October last year in TNO (Ref. 3).

Also two alternative models have been developed for the assessment of induced seismicity. The Strain Partitioning (SP) model was developed for the update of the winningsplan 2013 and has been described in the Addendum to the winningsplan 2013 (Ref. 1). During 2014, an alternative model was developed based on activity rates (AR). A draft report describing this model has been shared (on 20th October 2014) with experts in SodM, KNMI and TNO. This AR model has been independently reviewed by an independent expert (Dr. Ian Main) and discussed at a workshop SodM, KNMI and TNO (29th October).

Surface accelerations were calculated using the methodology described in the Addendum to the winningsplan 2013 (Ref. 1).

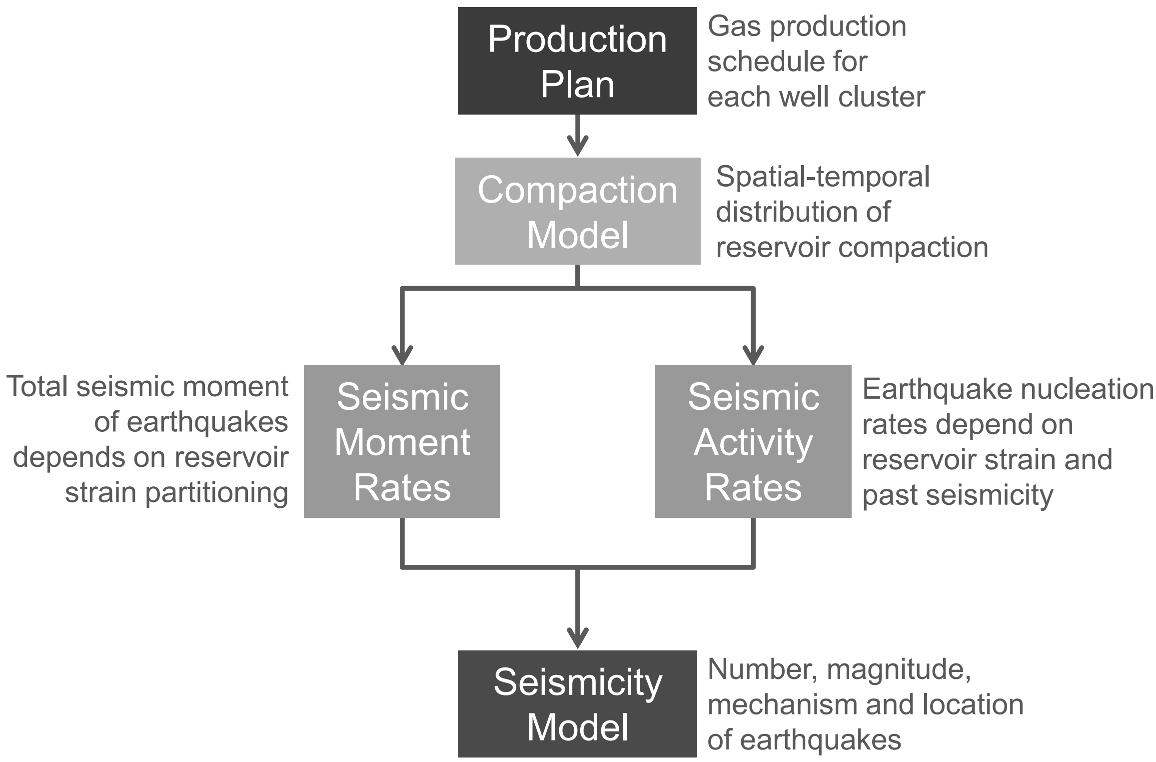


Figure 36 Two alternative seismicity models have been prepared.

The scenario table below shows the sensitivity parameters and the alternatives.

Sub-surface Realization Model	**Compaction Model**	**Seismicity Model**	**Production from the Eemskanaal Cluster** [mln Nm^3/day]
Winningsplan 2013 (G1) and (M0)	Time-decay Model (TD)	Strain Partitioning Model	3
History match update Model 1 (STR 40)	Rate Type Compaction isotach Model (RTCiM)	Activity Rate Model	5
History match update Model 2 (STR 38)			8

Figure 37 Scenario table for the hazard assessment in the Eemskanaal area.

Probabilistic Seismic Hazard Assessments

Probabilistic Seismic Hazard Assessment (PSHA) is the convolution of a seismological model with a ground motion prediction equation (GMPE) to yield the ground motion with a given probability of exceedance at a given surface location. The PSHA results documented here pertain to all surface locations within a 36 X 25 km region around the Eemskanaal gas production cluster. Ground motion is measured according to the peak ground acceleration (PGA) expressed as a fraction of the acceleration due to gravity (g). The assessment period is from 1st January 2014 to 1st January 2017. A single GMPE is considered; this is identical to that used in previous assessments.

Two alternative seismological models are considered; the Strain Partitioning (SP) and the Activity Rate (AR) models. Both seismological models are conditioned on reservoir compaction models. Two alternative reservoir compaction models are also considered; the Time-decay (TD) and the Rate Type Compaction Isotach (RTCiM) models. Furthermore these compaction models are conditioned on the static and dynamic reservoir models and the future gas production plan. A wide range of alternative cases are also considered for these as documented in Appendix Table.

These assessments are based on 105 Monte Carlo simulations of $M \geq 1.5$ earthquakes and ground motions due to $M \geq 2.5$ earthquakes during the assessment period. Due to the stochastic nature of these simulations the results remain subject to residual random variability associated with the finite number of simulations performed. Based on the outcome of sensitivity tests residual random variability is estimated to be approximately 0.01 g. This random variability may, in principle, be reduced by significantly increasing the number of simulations. However, this requires significantly more simulation time and would necessarily limit the number of alternative scenarios that could be investigated within the time available.

The Eemskanaal gas production cluster is located at (241.539, 584.421). All map coordinates are given as kilometers within the Dutch National triangulation coordinates system (Rijksdriehoek).

Reference Model

As a reference the hazard assessment for the Eemskanaal area was also performed for the model and production schedule used in the update of the winningsplan 2013.

Results of the hazard assessment in Peak Ground Acceleration (PGA (g)) for the Eemskanaal area are shown for exceedance levels of 0.2%, 2% and 10% per annum in figures 38, 39 and 40. The RCTiM model and Strain Partitioning model have been used in this Reference Case. The RTCiM model was not yet available when preparing the update of the winningsplan 2013 (instead the Linear Isotachen model was used).

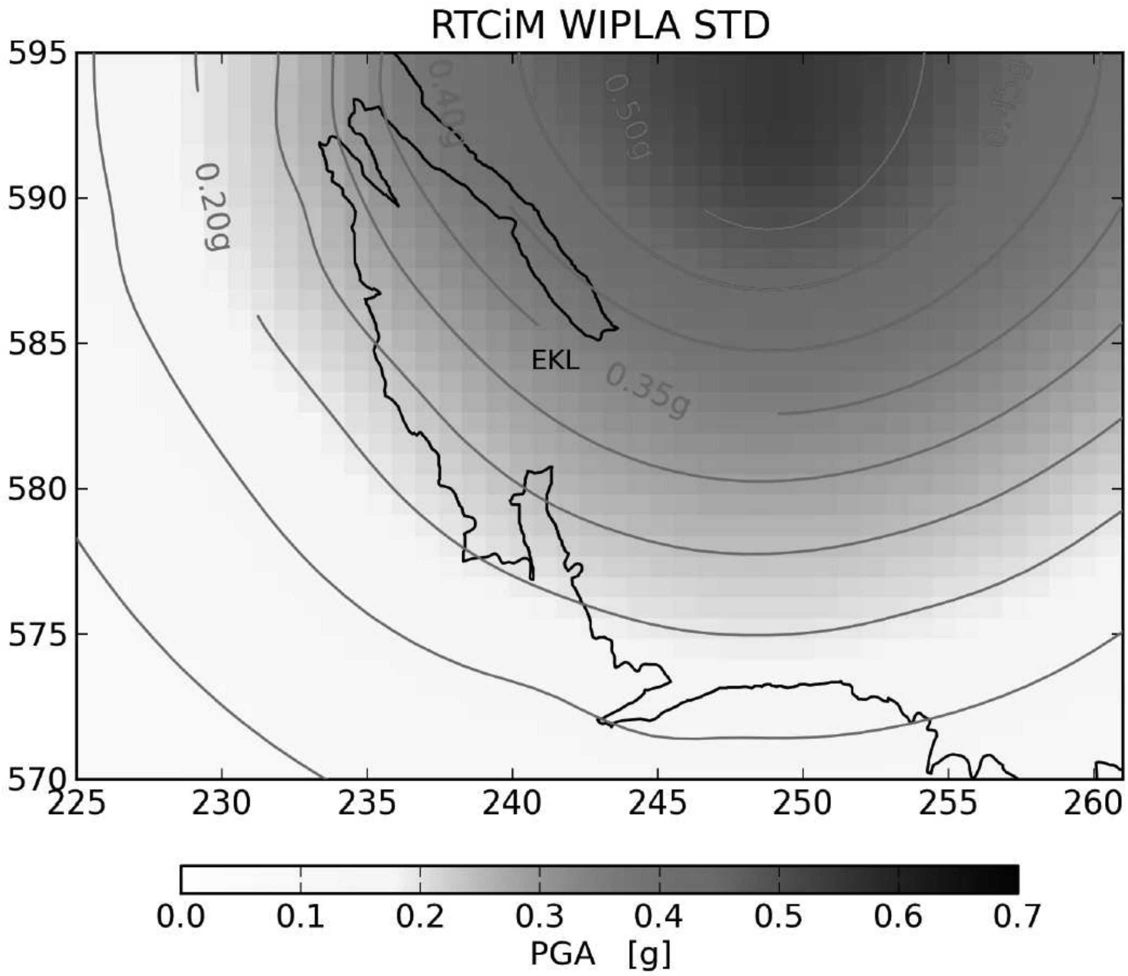


Figure 38 Hazard map showing the peak ground acceleration (PGA) with 0.2% average annual chance of exceedance from 2014 to 2017 and the Strain Partitioning seismological model. The contour interval is 0.05g.

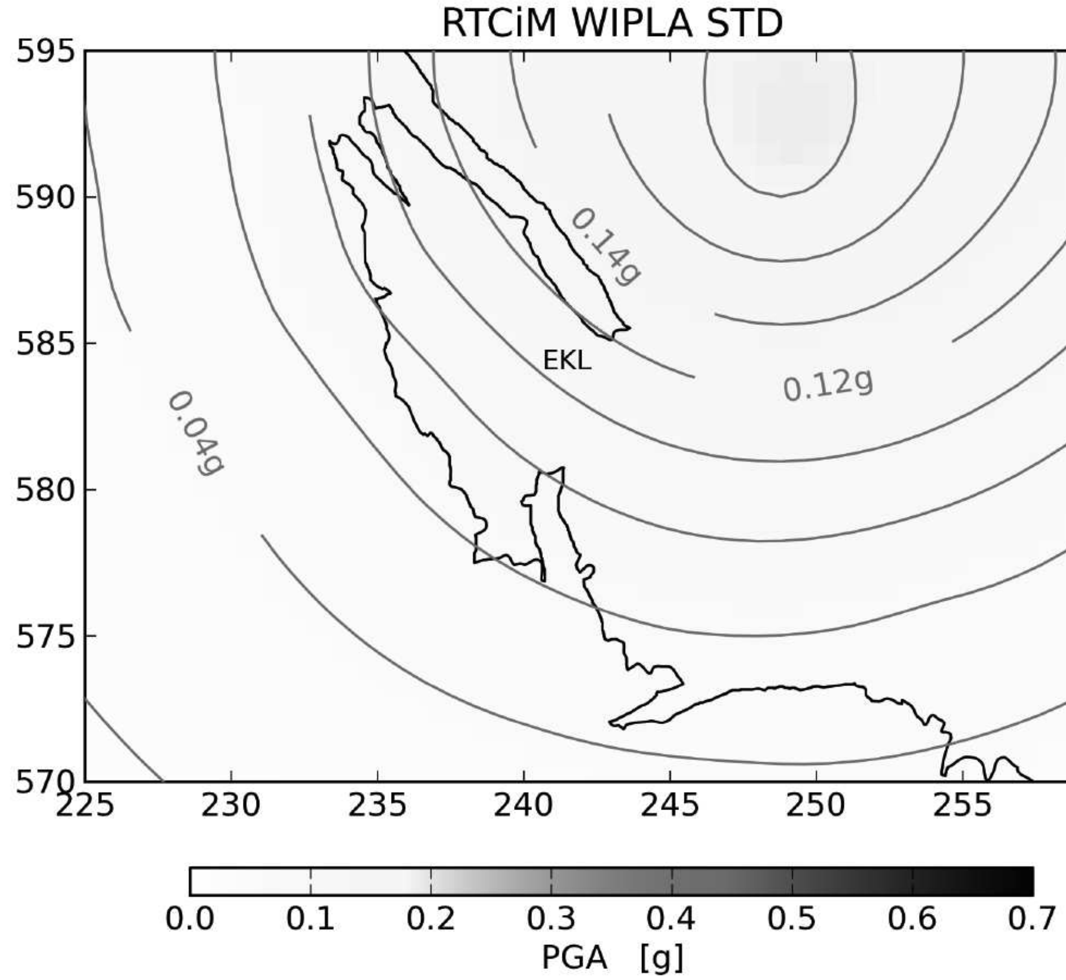


Figure 39 *Hazard map showing the peak ground acceleration (PGA) with 2% average annual chance of exceedance from 2014 to 2017 and the Strain Partitioning seismological model. The contour interval is 0.02g.*

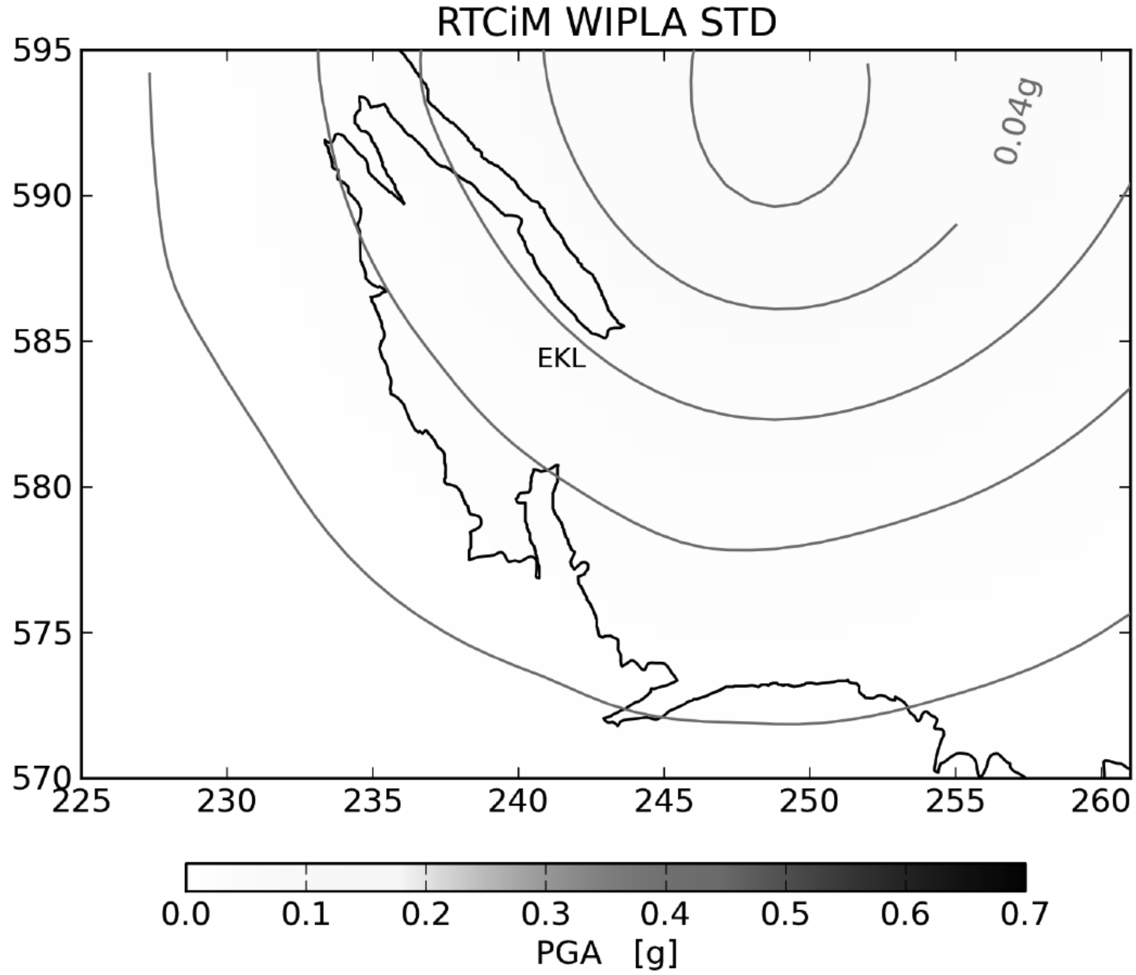


Figure 40 Hazard map showing the peak ground acceleration (PGA) with 10% average annual chance of exceedance from 2014 to 2017 and the Strain Partitioning seismological model. The contour interval is 0.01g.

As a reference peak ground acceleration (PGA) at the location of the Eemskanaal Cluster are 0.34 g, 0.11 g and 0.03 g for exceedance levels 0.2%, 2% and 10% respectively.

Base Case Model

As base case for this hazard assessment and associated sensitivities, the sub-surface model 1 (STR 40), the RTCiM Compaction Model and Strain Partitioning Seismogenic model were used. A production level of 8 mln Nm^3/day (see Section The Eemskanaal Cluster of Groningen) was chosen. Results of the hazard assessment in Peak Ground Acceleration (PGA (g)) for the Eemskanaal area are shown for exceedance levels of 0.2%, 2% and 10% per annum in figures 41, 43 and 43.

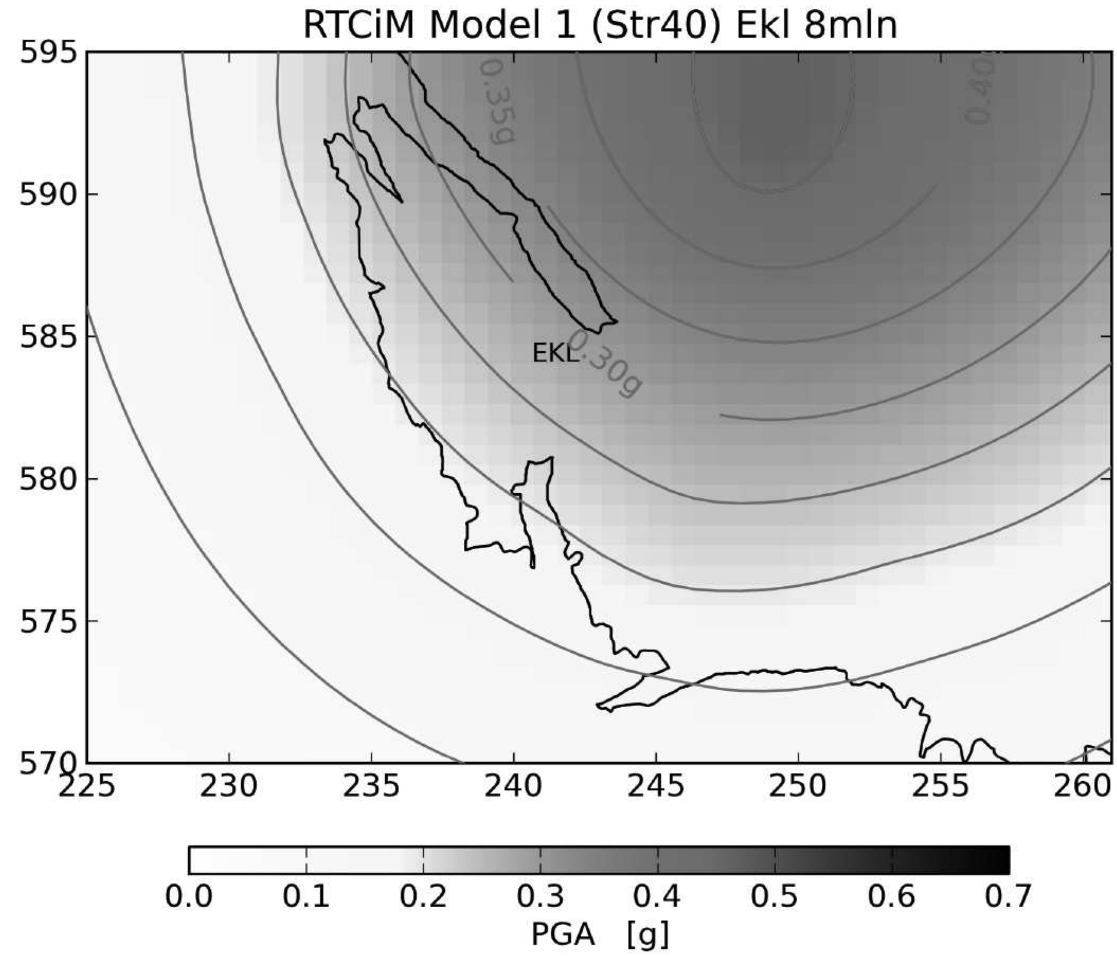


Figure 41 Hazard map showing the peak ground acceleration (PGA) with 0.2% average annual chance of exceedance from 2014 to 2017 and the Strain Partitioning seismological model. The contour interval is 0.05g.

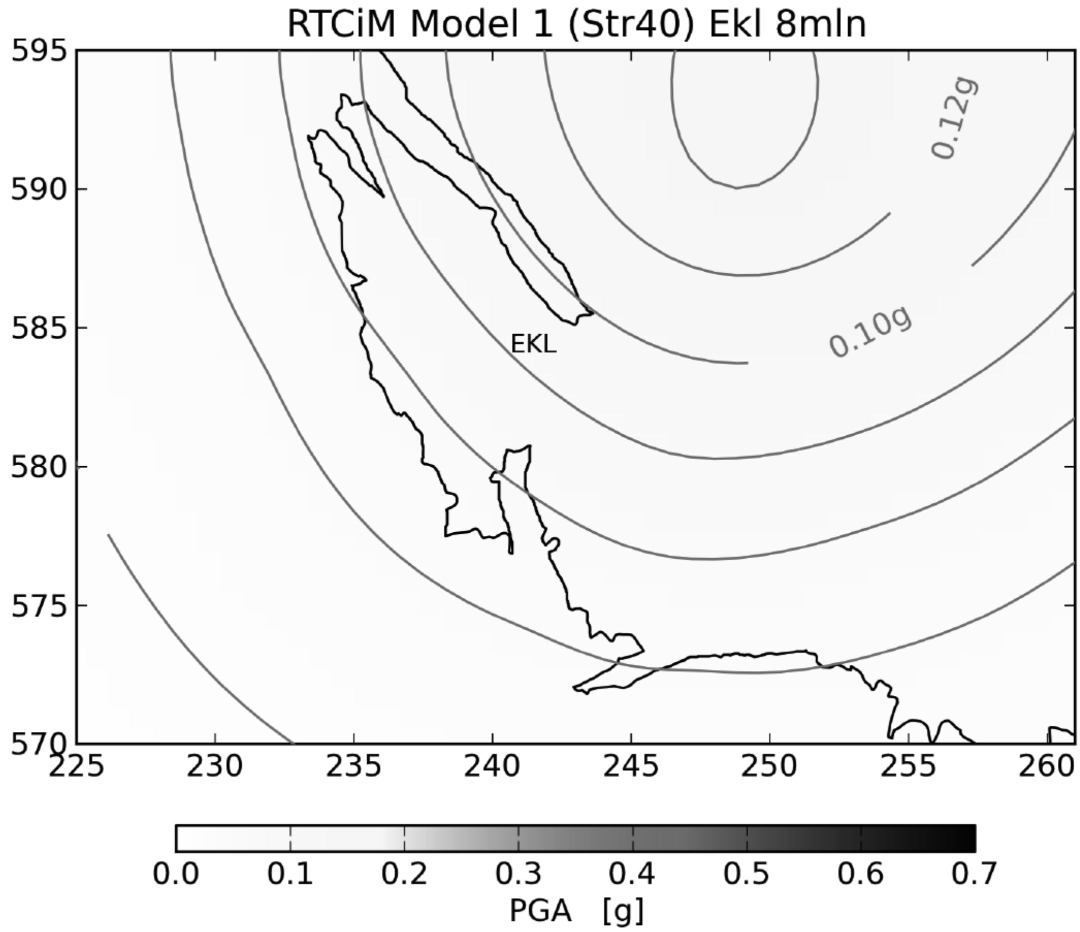


Figure 42 Hazard map showing the peak ground acceleration (PGA) with 2% average annual chance of exceedance from 2014 to 2017 and the Strain Partitioning seismological model. The contour interval is 0.02g.